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RANS CFD simulations of flow around Bolund

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Presentations from “The Bolund Experiment: Workshop” 3-4th December 2009

Risø-R-Report

Edited by Andreas Bechmann
Risø-R-1745(EN)
August 2010

Risø DTU
National Laboratory for Sustainable Energy

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Title: Presentations from "The Bolund Experiment: Workshop" 3-4th December 2009
Division: Division of Wind Energy

Risø-R-1745(EN)
August 2010

Abstract (max. 2000 char.):

This report contain copies of the presentations given at "The Bolund Experiment: Workshop" held on the 3-4th December 2009 at Risø DTU. The agenda of the two days and a participant list is given before the presentations.

The workshop was held as part of the EFP project "Metoder til kortlægning af vindforholdene i komplekst terræn".

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Contents

1 Introduction

The wind industry is increasingly relying on a large number of different micro-scale models for resource assessment of sites in complex terrain. There is, however, no consensus from the wind energy community on a standardized methodology for resource assessment modeling. The difficulties in providing guidelines are twofold: The experimental data available for validating the flow models is very limited and no systematic comparison of different flow models exist. With the Bolund Experiment both of these difficulties are approached.

The Bolund experiment is a measuring campaign from a complex terrain performed in 2007 and 2008 where high frequency data from 35 anemometers provides a unique database designed to validate micro-scale flow models [1]. Since no systematic comparison of micro-scale models existed it was decided to challenge micro-scale modelers to simulate the wind over Bolund and compare the results systematically. Since the Bolund measurements had not been published the comparison could be made blindly, i.e. the participants would not have prior knowledge of the measurement results. To broaden the types of models participating, modelers were invited worldwide from research institutes, universities and industry. More than 40 groups participated in the blind comparison with well over 50 model predictions and the blind comparison therefore gives an overview of the accuracy of micro-scale models anno 2010.

On the 3-4 December 2009, 80 specialists in modeling of wind over complex terrain meet at a Risø DTU workshop where the model predictions and the Bolund measurements were revealed. During the workshop, interesting presentations were given about different flow modeling approaches. This report contains copies of the presentations given at the workshop.

[1] A. Bechmann, J. Berg, M.S. Courtney, H.E. Jørgensen, J. Mann and N.N. Sørensen. *The bolund experiment: Overview and background.* Technical Report Risø-R1658(EN), Risø DTU, National Lab., Roskilde, Denmark, 2009.

1.1 Agenda

Below the agenda for the two day workshop is given. The topics of the first day were related to the Bolund experiment and blind comparison while the second day was about different micro-scale modelling approaches.

Program

Thursday December 3

9:00	Registration / Coffee
9:30	Welcome
9:45	**The Askervein Experiment** *Peter A. Taylor, York University*
10:30	Coffee
10:40	**The Bolund Experiment** *J. Berg, J. Mann & H.E. Jørgensen, Risø DTU*
12:10	**Group Photo**
12:30	Lunch
13:30	**Blind Comparison Results** *Andreas Bechmann, Risø DTU*
14:45	Coffee
16:00	**Questions to Bolund Team**
17:00	Bus to Scandic Hotel & Dinner
19:00	**Conference Dinner** *Sponsored by Vestas Technology R&D*

Friday December 4

9:00	Resume / Coffee
9:15	**LES Simulation of Terrain** *Vijayant Kumar, Macquarie Capital* *Marc Parlange & Chad Higgins, EPFL*
10:00	Coffee
10:10	**Wind Tunnel Modeling of Bolund** *Brad C. Cochran, CPP Wind*
10:50	**RANS Simulation of Bolund** *Niels Sørensen, Risø DTU*
11:30	**Poster Introduction**
12:00	Lunch + Poster / Coffee
14:00	**Panel Discussion: Flow modeling** *Peter Taylor, Brad Cochran, Vijayant Kumar* *Niels Sørensen, Jakob Mann*
15:45	Close

1.2 Participants

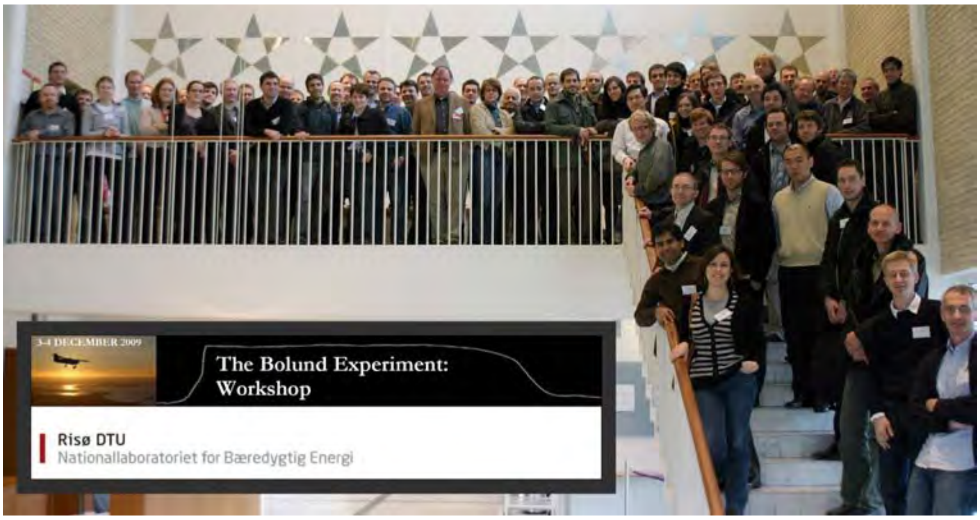
About 80 participants joined the workshop to discuss the results of the blind comparison. We want to thank you all for your positive and constructive attitudes and for making it a memorable event. Below, the workshop participants are listed. Many of the workshop participants also participated in the blind comparison but it has been chosen to keep the participants of the comparison anonymous. We would like to give special thanks for some very interesting presentation to the three invited speakers:

Peter A. Taylor (York University, Zephyr North Canada)
Vijayant Kumar (Macquarie Holdings)
Brad C. Cochran (CPP, inc.)

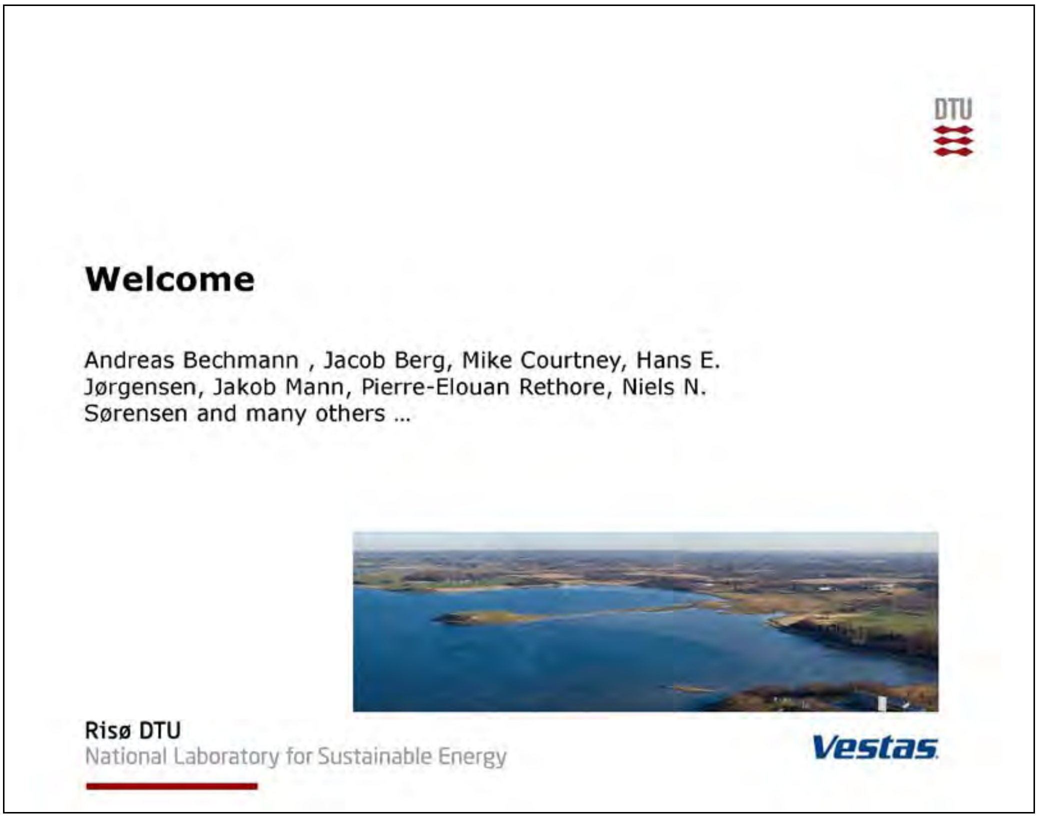
Participant list:

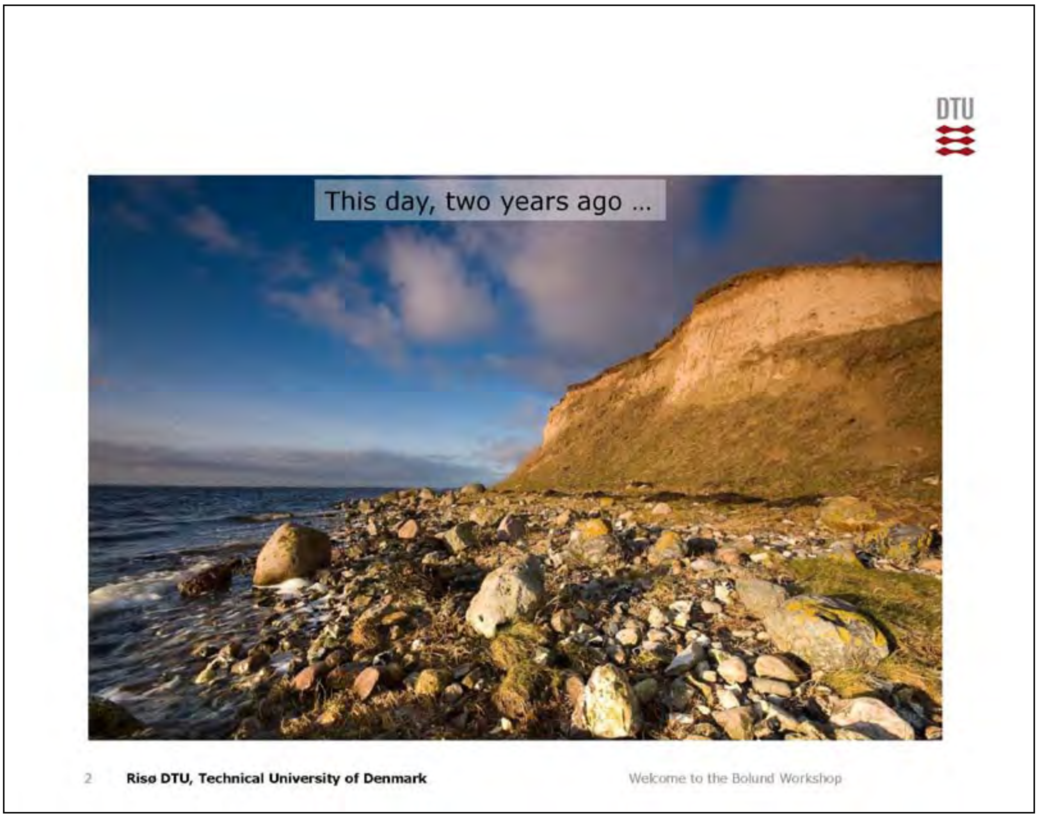
Christiane Montavon	ANSYS UK Ltd
Steve Evans	CD-adapco
Dennis Nagy	CD-adapco
Bibiana García	CENER
Javier Sanz Rodrigo	CENER
John Prospathopoulos	Centre for Renewable Energy Sources and Saving
Brad Cochran	CPP
Rémi Gandoin	DONG Energy
Jonathon Sumner	Ecole de technologie superieure
Per Nielsen	EMD International A/S
Morten Lybech Thøgersen	EMD International A/S
Hanne Thomassen	Energistyrelsen
Mario Benso	EREDA
Carlos Hernandez Medina	EREDA
Moreira Raquel	EREDA
Anja Geiger	ETHZ, GWH
Paolo Muscionico	ETHZ, GWH
Pascal Podstransky	ETHZ, GWH
Jose Laginha Palma	FEUP/ CEsA
Thomas Hahm	Fluid & Energy Engineering GmbH & Co. KG
Steffen Wussow	Fluid & Energy Engineering GmbH & Co. KG
Sharad Tripathi	FLUIDYN
Lars Landberg	Garrad Hassan and Partners Ltd
Joel Manning	Garrad Hassan and Partners Ltd
Richard Whiting	Garrad Hassan and Partners Ltd
Per Österdahl	Go Virtual Nordic AB
Sven Perzon	Go Virtual Nordic AB
Michael Schatzmann	Hamburg University
Espen Åkervik	Kjeller Vindteknikk AS
Ove Undheim	Kjeller Vindteknikk AS
Vijayant Kumar	Macquarie Capital
Roshan Oberoi	Metacomp Technologies, Inc.
Céline Bezault	MeteoDyn
Stephane Popinet	National Insititute of Water and Atmospheric research (NIWA)
Ferran Palau	Normawind
Keld Olsen	Råd. Ing. Keld E. Olsen
Gerd Habenicht	RES
Andreas Bechmann	Risø DTU
Jacob Berg	Risø DTU
Jesper Grønnegaard Pedersen	Risø DTU
Per Hansen	Risø DTU
Poul Hummelshøj	Risø DTU
Niels Otto Jensen	Risø DTU
Hans E. Jørgensen	Risø DTU

Georgios Mandrekas	Risø DTU
Jakob Mann	Risø DTU
Pierre-Elouan Mikael Rethore	Risø DTU
Morten Nielsen	Risø DTU
Niels Nørmark Sørensen	Risø DTU
Andrey Sogachev	Risø DTU
Frederik Zahle	Risø DTU
Flemming Rasmussen	Risø DTU
Ib Troen	Risø DTU
Corinne Weaver	RWE Npower Renewables Ltd
Jeppe Johansen	Siemens Wind Power
Jesper Laursen	Siemens Wind Power
Kasper Mortensen	Siemens Wind Power
Morten Rams Quistgaard	Siemens Wind Power
Brian Broe	Suzlon Wind Energy A/S
Jørgen Højstrup	Suzlon Wind Energy A/S
Monika Polster	TÜV NORD Systec GmbH & Co. KG
Mathias Cehlin	Vattenfall Research & Development AB
Jens Madsen	Vattenfall Research & Development AB
Ylva Odemark	Vattenfall Research & Development AB
Javier Püvi	Vestas Mediterranean
Roberto Sánchez	Vestas Mediterranean
Mark Zagar	Vestas Wind & Site Competence Centre
Søren Holm Mogensen	Vestas Wind Systems A/S
Yavor Hristov	Vestas Wind Systems A/S
Cheng-Hu Hu	Vestas Wind Systems A/S
Gregory Oxley	Vestas Wind Systems A/S
Arne Gravdahl	WindSim AS
David Weir	WindSim AS
Xiao Yu	York University
Peter Taylor	York University
Wengsong Weng	York University



“Welcome” - by Andreas Bechmann





3 **Risø DTU, Technical University of Denmark** Welcome to the Bolund Workshop

4 **Risø DTU, Technical University of Denmark** Welcome to the Bolund Workshop

5 **Risø DTU, Technical University of Denmark** Welcome to the Bolund Workshop

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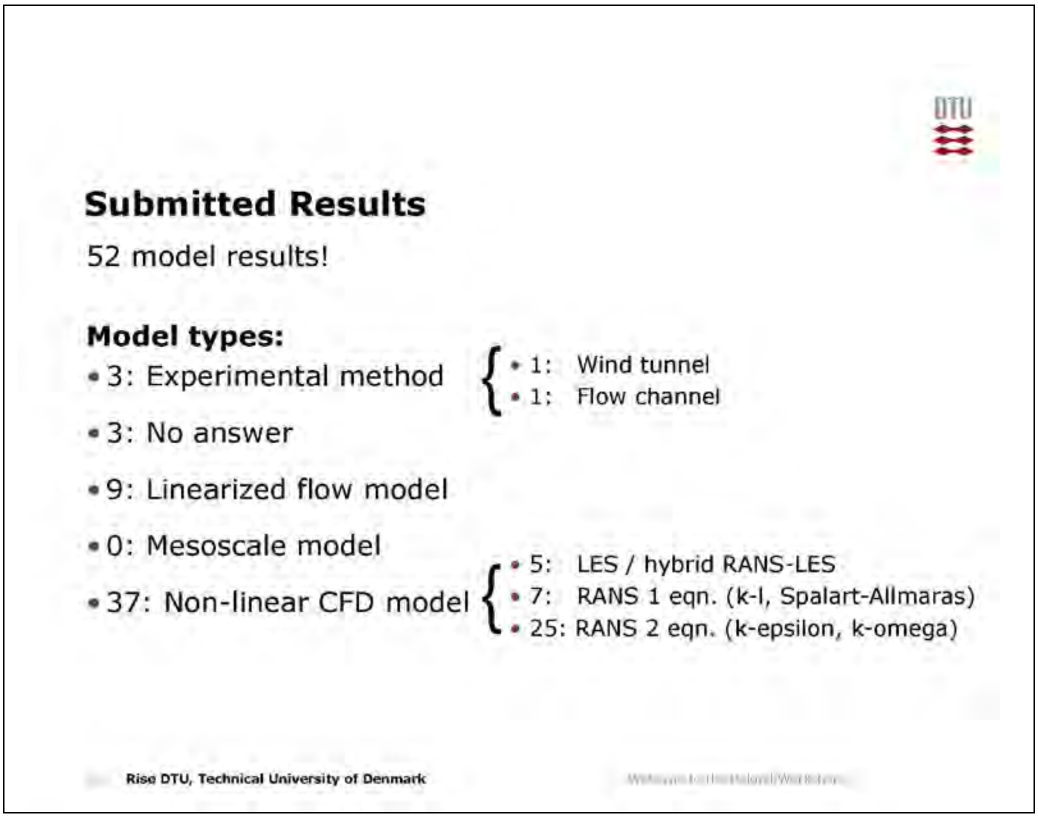
10 **Risø DTU, Technical University of Denmark** Welcome to the Bolund Workshop

11 **Risø DTU, Technical University of Denmark** Welcome to the Bolund Workshop

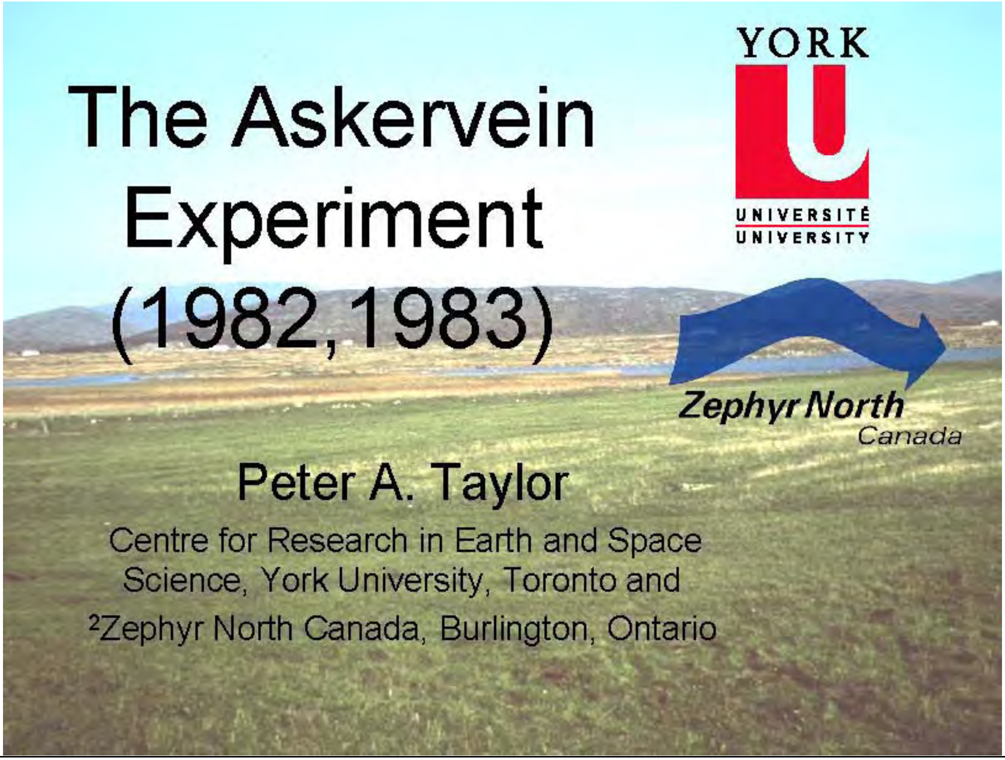
Thank You!

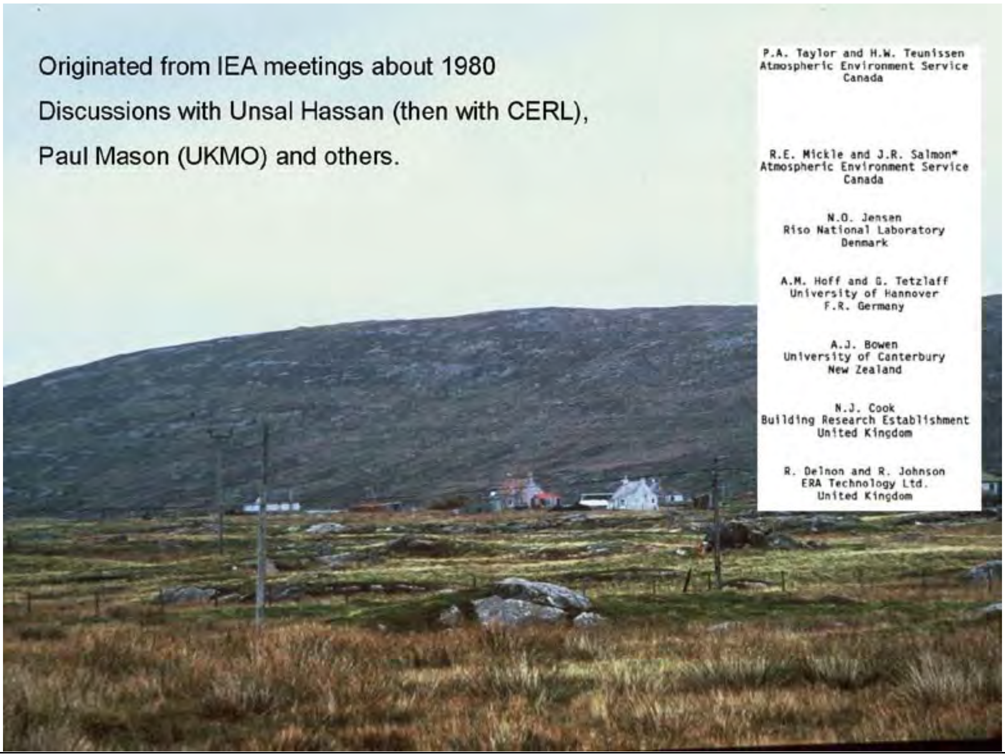
- **Energistyrelsen (Danish Energy Agency)**
- **Vestas Technology R&D**
- **Thank you modelers!**
  Preparation time: 652 hours
  Comp. time: 587 days

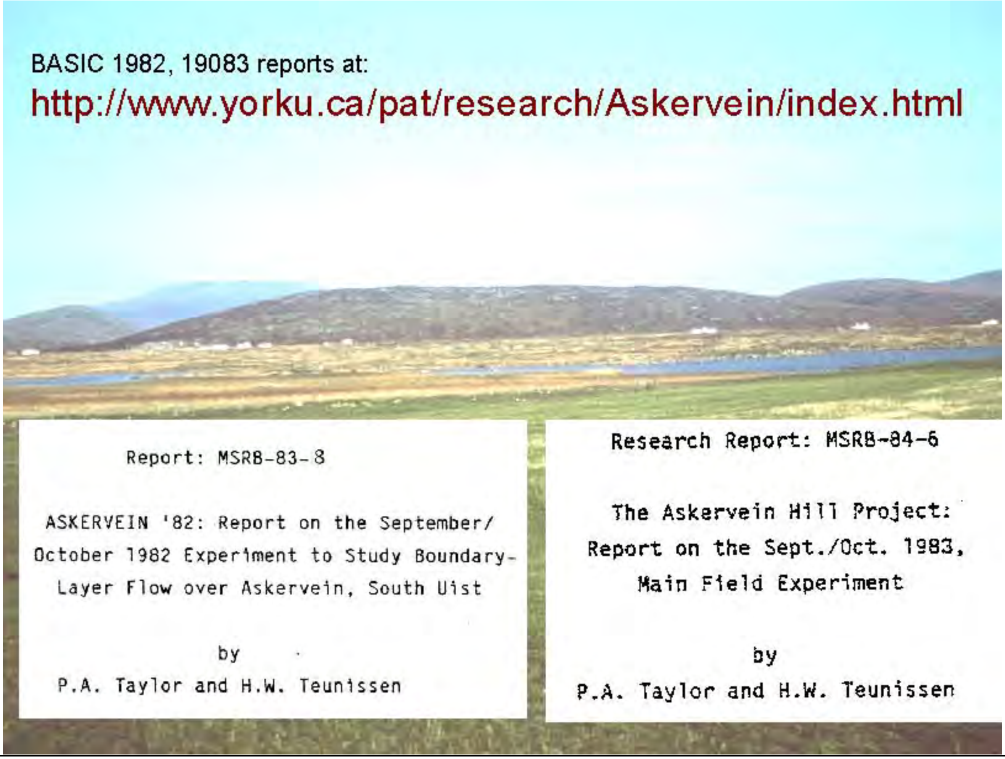
Risø DTU, Technical University of Denmark

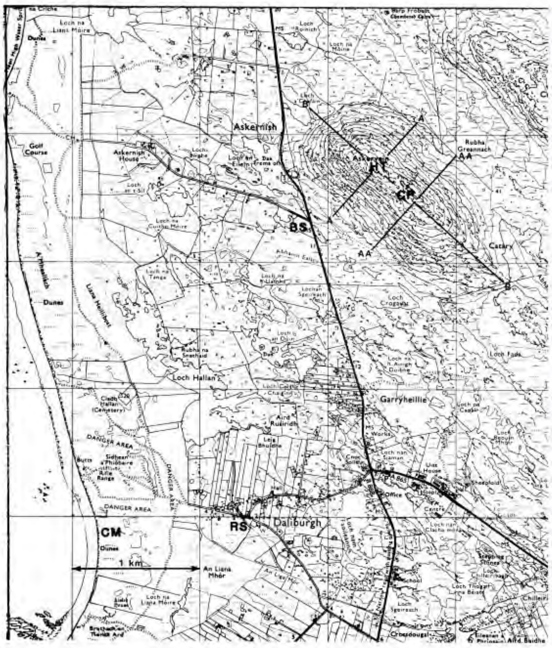

Submitted Results
52 model results!
Model types:
• 3: Experimental method
• 1: Wind tunnel
• 1: Flow channel
• 3: No answer
• 9: Linearized flow model
• 0: Mesoscale model
• 37: Non-linear CFD model
• 5: LES / hybrid RANS-LES
• 7: RANS 1 eqn. (k-l, Spalart-Allmaras)
• 25: RANS 2 eqn. (k-epsilon, k-omega)
Risø DTU, Technical University of Denmark

“The Askervein Experiment” - by Peter A. Taylor









Ordance Survey Map that we had in 1982

Google Earth 2009. HT
57°11'16.63"N, 7°22'45.07"W

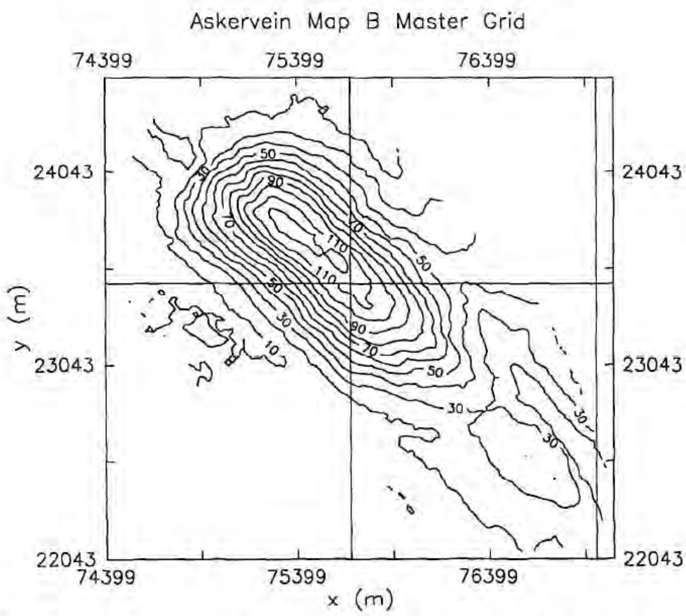
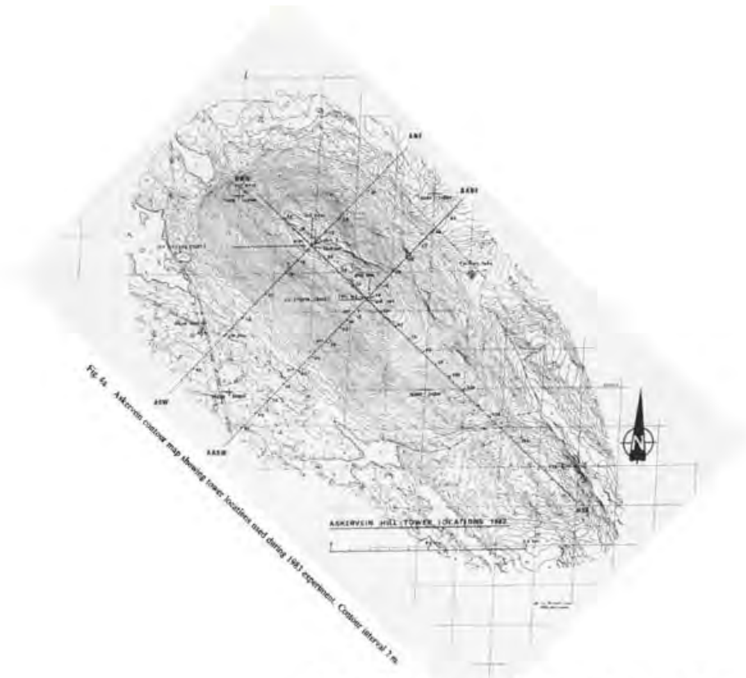


Figure 2. Same as Figure 1 except the area covered is referred to in the text as *Map B* and the original contour map was specially prepared for the Askervein study at a scale of 1:5 000: see text for further details. Heights are in metres above sea level and the contour interval is 10 m. Topographic features to the north and east of Askervein have been blanked out as they were incomplete on the original map.



I should have a better copy somewhere!!!

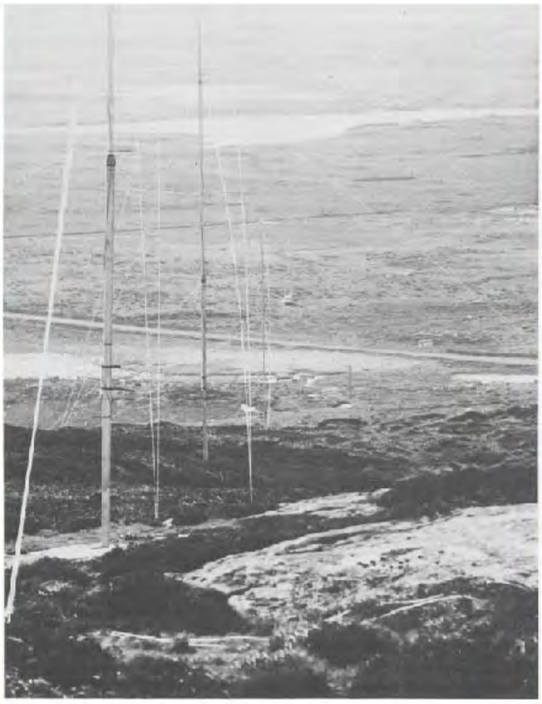
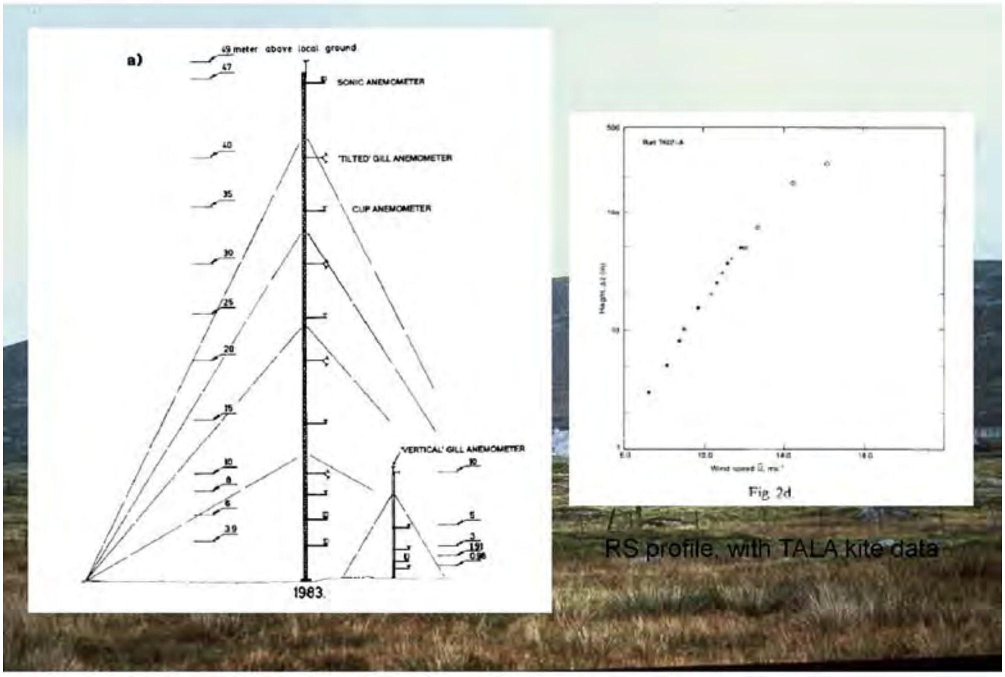


Fig. 1   Photograph of 10 m mean flow posts deployed along the A line during the Askervein '82 experiment.

Instrumentation

- Lots of cup anemometers, mostly on about fifty 10-m posts – Gill, Casella, Vector, Friedrichs
- Gill UVW propeller anemometers – signal conditioning problems. RM Young windmonitor
- TALA kites, single (Peter Taylor et al) and multiple (Nick Cook)
- Sonics (Risø + AES, Hans Teunissen) Radiosondes
- 50-m towers at HT and RS, 30-m tower near upwind base of hill.
- Data acquisition! Computers and lots of magnetic tape in hilltop caravan and Reference station shed. Sea Data tape loggers. Pulse counters, electronic and mechanical (Casella anemometers)



Boundary-Layer Meteorology: Search, Askervein – 31 papers

BOUNDARY-LAYER FLOW OVER TOPOGRAPHY: IMPACTS OF THE ASKERVEIN STUDY

JOHN L. WALMSLEY
Atmospheric Environment Service, Downsview, Ontario M3H 5T4 Canada
and
PETER A. TAYLOR
Department of Earth and Atmospheric Science, York University, North York, Ontario M3J IP3
Canada
(Received in final form 20 October, 1995)

Abstract. One of the objectives of the Askervein Hill Project was to obtain a comprehensive and accurate dataset for verification of models of flow and turbulence over low hills. In the present paper, a retrospective of the 1982 and 1983 Askervein experiments is presented. The field study is described in brief and is related to similar studies conducted in the early 1980s. Data limitations are discussed and applications of numerical and wind-tunnel models to Askervein are outlined. Problems associated with model simulations are noted and model results are compared with the field measurements.

27. Article The Askervein Hill project: Overview and background data
P. A. Taylor and H. W. Teunissen
The Askervein Hill project was a collaborative study of boundary-layer flow over low... Volume 39, Numbers 1-2 / April, 1987 PDF (4.8 KB)

26. Article The Askervein Hill Project: Mean wind variations at fixed heights above ground J. R. Salmon, A. J. Bowen, A. M. Hoff, R. Johnson, R. E. Mickle, P. A. Taylor, G. Tetzlaff and J. L. Walmsley
This is one of a series of papers on the Askervein Hill Project. It presents results on the variations in mean wind speed...Volume 43, Number 3 / May, 1988 PDF (1.9 MB)

28. Article The Askervein Hill Project: Vertical profiles of wind and turbulence R. E. Mickle, N. J. Cook, A. M. Hoff, N. O. Jensen, J. R. Salmon, P. A. Taylor, G. Tetzlaff and H. W. Teunissen
This is one of a series of papers on the Askervein Hill Project. It presents results from the Askervein 1982 and 1983 experiments...
Volume 43, Numbers 1-2 / April, 1988 PDF (1.6 MB)

BOUNDARY-LAYER FLOW OVER LOW HILLS

*(A Review)**

Boundary-Layer Meteorology **39** (1987) 107–132.

P. A. TAYLOR
Boundary-Layer Research Division, Atmospheric Environment Service, Downsview, Canada
P. J. MASON
Meteorological Office, Bracknell, England
and
E. F. BRADLEY
CSIRO Division of Environmental Mechanics, Black Mountain, Canberra, Australia

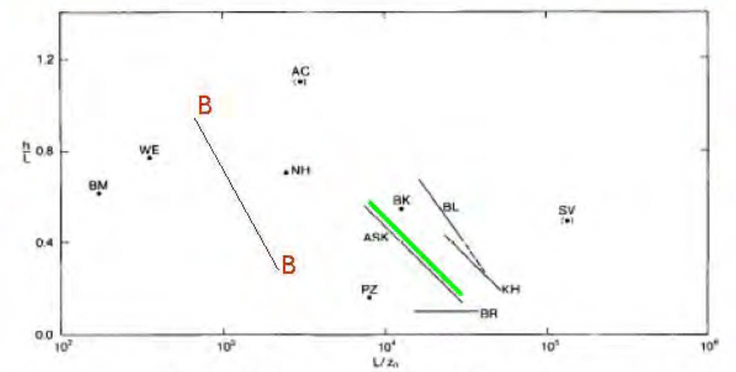


Fig. 3. Parameter space diagram – field studies of boundary-layer flow over hills. See Table I for additional details.

Bolund, L/z_0 = 0.73-3.7 x 10^3: h/L = 1.0-0.2; h = 10.9 m, L was not well defined – not the simple hill we had looked for in 1980s. Note that L is upwind distance to point where z_s = h/2.

Run TU-03B, Φ = 210 , October 1983

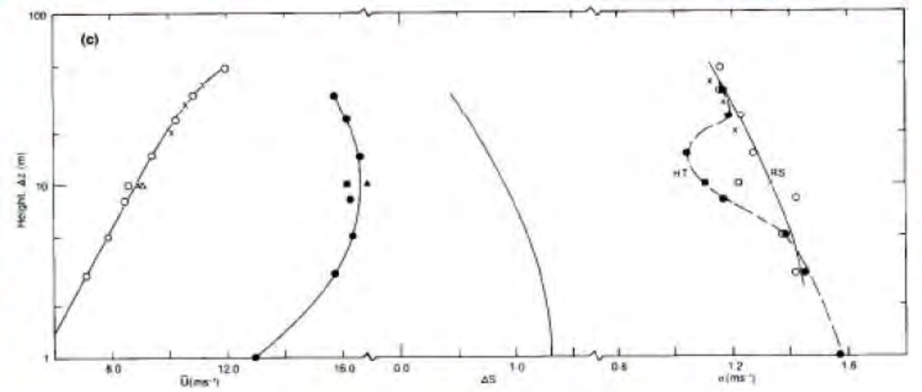
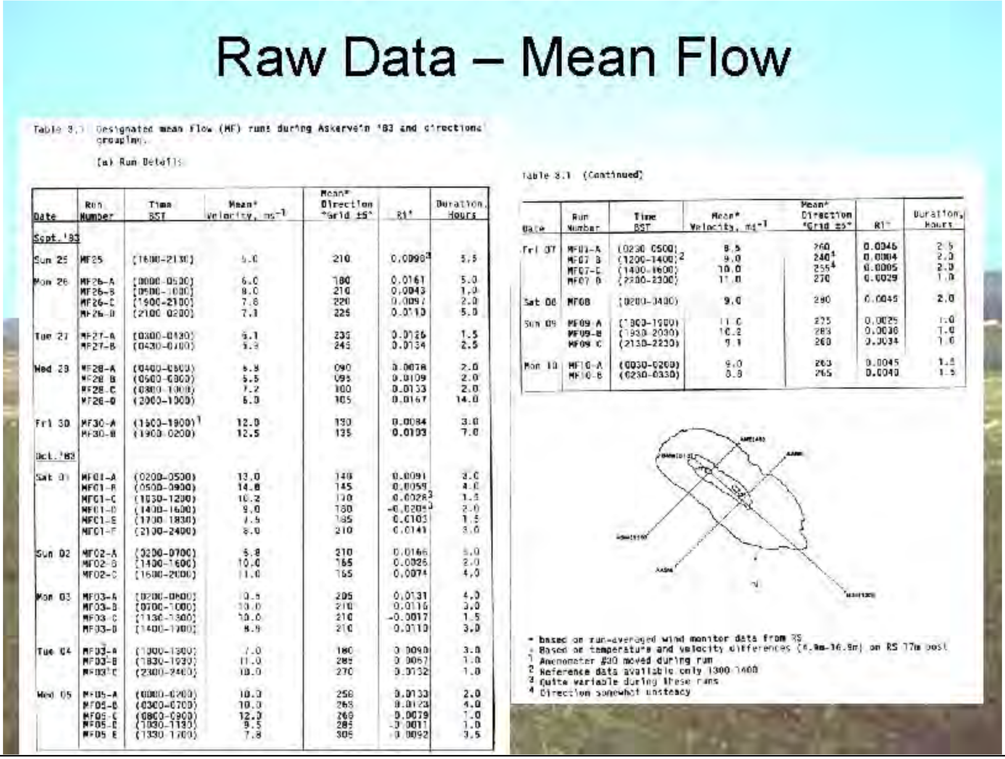


Fig. 6c.

Date	Run number	Time (BST)	Duration (hr)	Mean wind at RS [a]	RS profile data [b]		Ri [c]	$z/\mathscr{L}$ [d]
					u_* (m s^{-1})	z_0 (m)		
Mon03	TU03–A	1200–1300	1.0	210/9.8	0.63	0.022	−0.0038	−0.015
	–B	1400–1700	3.0	210/8.9	0.57	0.020	−0.0074	−0.004



Raw Data – Mean Flow

Table 3.1 Designated mean flow (MF) runs during Askervein '83 and directional grouping.

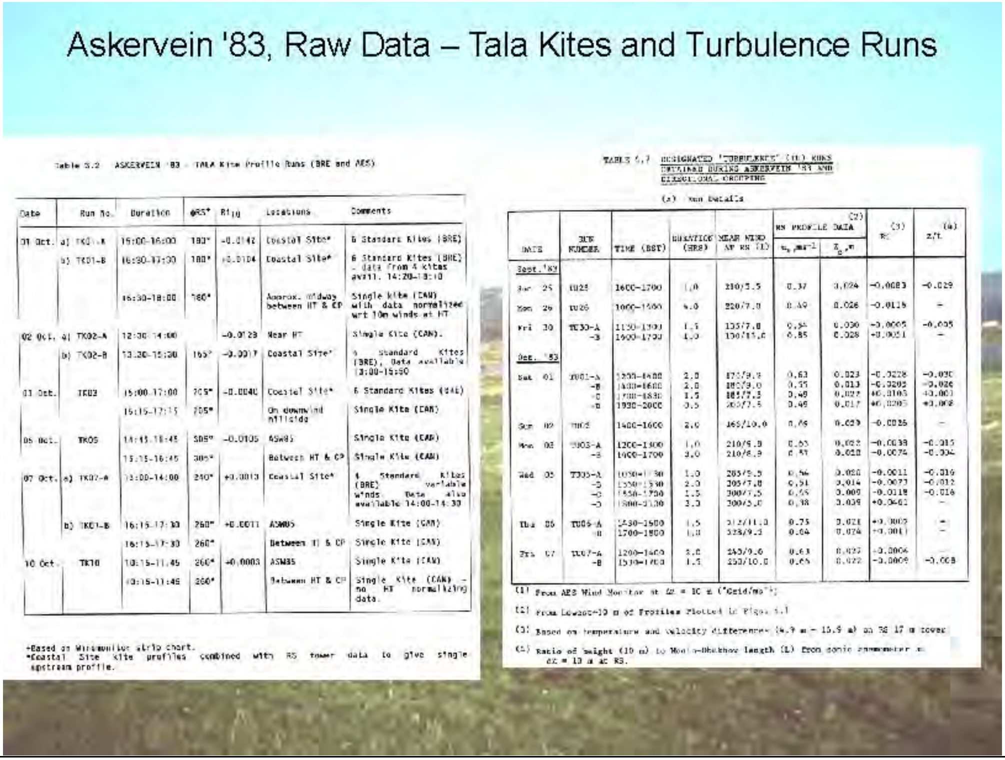
(a) Run Details

Date	Run Number	Time BST	Mean* Velocity, ms^{-1}	Mean* Direction °Grid ±5°	Ri⁺	Duration, Hours
Sept. '83						
Sun 25	MF25	(1600–2130)	5.0	210	0.0098[3]	5.5
Mon 26	MF26-A	(0000–0500)	6.0	180	0.0161	5.0
	MF26-B	(0500–1000)	8.0	210	0.0043	1.0
	MF26-C	(1900–2100)	7.8	220	0.0097	2.0
	MF26-D	(2100–0200)	7.1	225	0.0110	5.0
Tue 27	MF27-A	(0300–0430)	6.1	235	0.0126	1.5
	MF27-B	(0430–0700)	5.9	245	0.0134	2.5
Wed 28	MF28-A	(0400–0600)	6.8	090	0.0078	2.0
	MF28-B	(0600–0800)	5.5	095	0.0109	2.0
	MF28-C	(0800–1000)	7.2	100	0.0133	2.0
	MF28-D	(2000–1000)	6.0	105	0.0167	14.0
Fri 30	MF30-A	(1500–1900)[1]	12.0	130	0.0084	3.0
	MF30-B	(1900–0200)	12.5	135	0.0103	7.0
Oct. '83						
Sat 01	MF01-A	(0200–0500)	13.0	140	0.0091	3.0
	MF01-B	(0500–0900)	14.8	145	0.0059	4.0
	MF01-C	(1030–1200)	10.2	170	0.0028[3]	1.5
	MF01-D	(1400–1600)	9.0	180	-0.0205[3]	2.0
	MF01-E	(1700–1830)	7.5	185	0.0103	1.5
	MF01-F	(2100–2400)	8.0	210	0.0141	3.0
Sun 02	MF02-A	(0200–0700)	6.8	210	0.0166	5.0
	MF02-B	(1400–1600)	10.0	165	0.0026	2.0
	MF02-C	(1600–2000)	11.0	165	0.0074	4.0
Mon 03	MF03-A	(0200–0600)	10.5	205	0.0131	4.0
	MF03-B	(0700–1000)	10.0	210	0.0116	3.0
	MF03-C	(1130–1300)	10.0	210	-0.0017	1.5
	MF03-D	(1400–1700)	8.9	210	0.0110	3.0
Tue 04	MF03-A	(1000–1300)	7.0	180	0.0090	3.0
	MF03-B	(1830–1930)	11.0	285	0.0067	1.0
	MF03-C	(2300–2400)	10.0	270	0.0132	1.0
Wed 05	MF05-A	(0000–0200)	10.0	258	0.0133	2.0
	MF05-B	(0300–0700)	10.0	265	0.0123	4.0
	MF05-C	(0800–0900)	12.0	260	0.0079	1.0
	MF05-D	(1030–1130)	9.5	285	-0.0011	1.0
	MF05-E	(1330–1700)	7.8	305	0.0092	3.5

Table 3.1 (Continued)

Date	Run Number	Time BST	Mean* Velocity, ms^{-1}	Mean* Direction °Grid ±5°	Ri⁺	Duration, Hours
Fri 07	MF07-A	(0230–0500)	8.5	260	0.0046	2.5
	MF07-B	(1200–1400)[2]	9.0	240[4]	0.0004	2.0
	MF07-C	(1400–1600)	10.0	255[4]	0.0005	2.0
	MF07-D	(2200–2300)	11.0	270	0.0029	1.0
Sat 08	MF08	(0200–0400)	9.0	280	0.0045	2.0
Sun 09	MF09-A	(1800–1900)	11.0	275	0.0025	1.0
	MF09-B	(1930–2030)	10.2	283	0.0030	1.0
	MF09-C	(2130–2230)	9.1	260	0.0034	1.0
Mon 10	MF10-A	(0030–0200)	9.0	263	0.0045	1.5
	MF10-B	(0230–0330)	8.8	265	0.0040	1.5

* based on run-averaged wind monitor data from RS
⁺ Based on temperature and velocity differences (4.9m–16.9m) on RS 17m post
[1] Anemometer #30 moved during run
[2] Reference data available only 1300–1400
[3] Quite variable during these runs
[4] Direction somewhat unsteady



Askervein '83, Raw Data – Tala Kites and Turbulence Runs

Table 3.2 ASKERVEIN '83 – TALA Kite Profile Runs (BRE and AES)

Date	Run No.	Duration	θRS⁺	Ri_{10}	Locations	Comments
01 Oct.	a) TK01-A	15:00–16:00	180°	-0.0142	Coastal Site*	6 Standard Kites (BRE)
	b) TK01-B	16:30–17:30	180°	+0.0104	Coastal Site*	6 Standard Kites (BRE) – data from 4 kites avail. 14:20–18:10
		16:30–18:00	180°		Approx. midway between HT & CP	Single kite (CAN) with data normalized wrt 10m winds at HT
02 Oct.	a) TK02-A	12:30–14:00		-0.0123	Near HT	Single Kite (CAN).
	b) TK02-B	13:20–15:30	165°	-0.0017	Coastal Site*	6 Standard Kites (BRE), Data available 13:00–15:50
03 Oct.	TK03	15:00–17:00	205°	-0.0040	Coastal Site*	6 Standard Kites (BRE)
		15:15–17:15	205°		On downwind hillside	Single Kite (CAN)
05 Oct.	TK05	14:45–16:45	305°	-0.0105	ASW85	Single Kite (CAN)
		15:15–16:45	305°		Between HT & CP	Single Kite (CAN)
07 Oct.	a) TK07-A	13:00–14:00	240°	+0.0013	Coastal Site*	4 Standard Kites (BRE) variable winds. Data also available 14:00–14:30
	b) TK07-B	16:15–17:30	260°	+0.0011	ASW85	Single Kite (CAN)
		16:15–17:30	260°		Between HT & CP	Single Kite (CAN)
10 Oct.	TK10	10:15–11:45	260°	+0.0003	ASW85	Single Kite (CAN)
		10:15–11:45	260°		Between HT & CP	Single Kite (CAN) – no HT normalizing data.

⁺Based on Windmonitor strip chart.
*Coastal Site kite profiles combined with RS tower data to give single upstream profile.

TABLE 3.? DESIGNATED 'TURBULENCE' (TU) RUNS OBTAINED DURING ASKERVEIN '83 AND DIRECTIONAL GROUPING

(a) Run Details

DATE	RUN NUMBER	TIME (BST)	DURATION (HRS)	MEAN WIND AT RS (1)	RS PROFILE DATA (2) u_*, ms^{-1}	RS PROFILE DATA (2) z_0, m	Ri (3)	z/L (4)
Sept. '83								
Sun 25	TU25	1600–1700	1.0	210/5.5	0.37	0.024	-0.0083	-0.029
Mon 26	TU26	1000–1500	5.0	220/7.0	0.49	0.026	-0.0115	–
Fri 30	TU30-A	1130–1300	1.5	135/7.8	0.54	0.030	-0.0005	-0.005
	-B	1600–1700	1.0	130/13.0	0.85	0.028	+0.0051	–
Oct. '83								
Sat 01	TU01-A	1200–1400	2.0	170/9.9	0.63	0.023	-0.0228	-0.030
	-B	1400–1600	2.0	180/9.0	0.55	0.013	-0.0205	-0.026
	-C	1700–1830	1.5	185/7.3	0.49	0.022	+0.0103	+0.001
	-D	1930–2000	0.5	205/7.5	0.49	0.017	+0.0205	+0.008
Sun 02	TU02	1400–1600	2.0	165/10.0	0.69	0.029	-0.0026	–
Mon 03	TU03-A	1200–1300	1.0	210/9.9	0.65	0.022	-0.0038	-0.015
	-B	1400–1700	3.0	210/8.9	0.57	0.020	-0.0074	-0.004
Wed 05	TU05-A	1030–1130	1.0	285/9.5	0.56	0.020	-0.0011	-0.016
	-B	1330–1530	2.0	305/7.8	0.51	0.014	-0.0073	-0.012
	-C	1550–1700	1.5	300/7.5	0.55	0.009	-0.0118	-0.016
	-D	1800–2130	3.3	300/5.0	0.38	0.039	+0.0461	–
Thu 06	TU06-A	1430–1600	1.5	312/11.0	0.75	0.021	+0.0002	–
	-B	1700–1800	1.0	328/9.3	0.64	0.024	+0.0011	–
Fri 07	TU07-A	1200–1400	2.0	245/9.6	0.63	0.022	+0.0006	–
	-B	1530–1700	1.5	253/10.0	0.65	0.022	-0.0009	-0.008

(1) From AES Wind Monitor at Δz = 10 m (°Grid/ms^{-1})
(2) From Lowest 10 m of Profiles Plotted in Figs. 3.1
(3) Based on temperature and velocity differences (4.9 m – 15.9 m) on RS 17 m tower
(4) Ratio of height (10 m) to Monin-Obukhov length (L) from sonic anemometer at Δz = 10 m at RS.

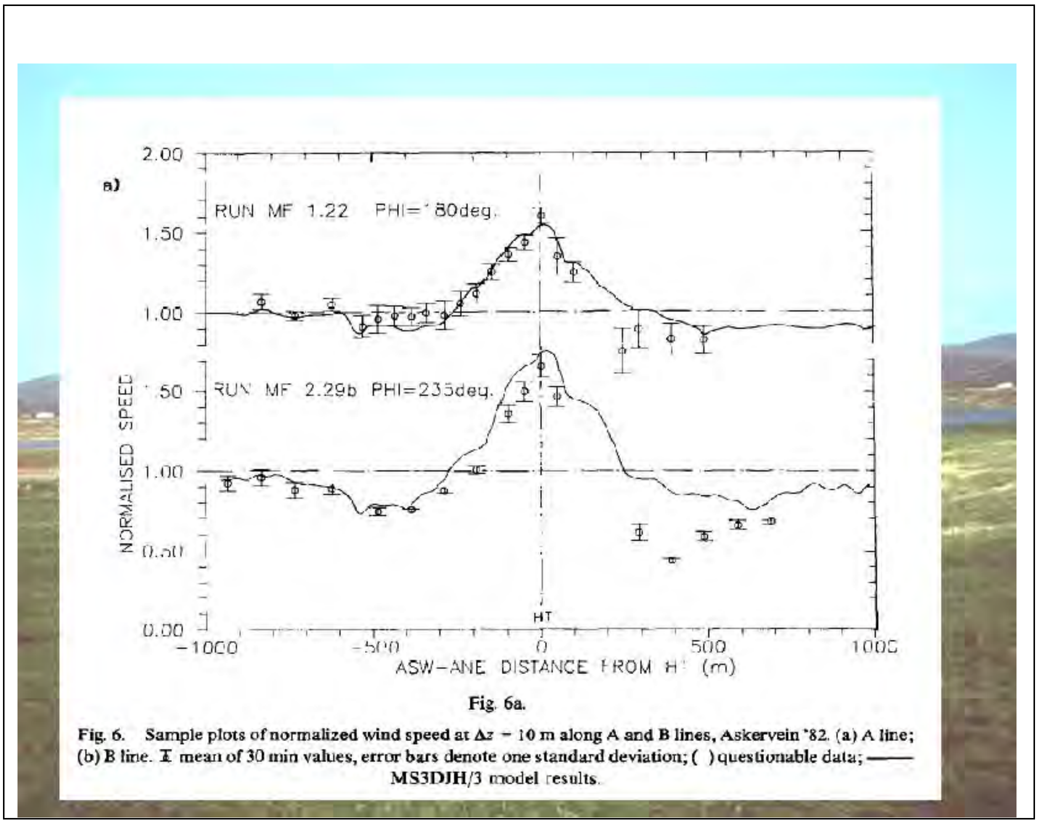


Fig. 6. Sample plots of normalized wind speed at Δz = 10 m along A and B lines, Askervein '82. (a) A line; (b) B line. I mean of 30 min values, error bars denote one standard deviation; ( ) questionable data; —— MS3DJH/3 model results.

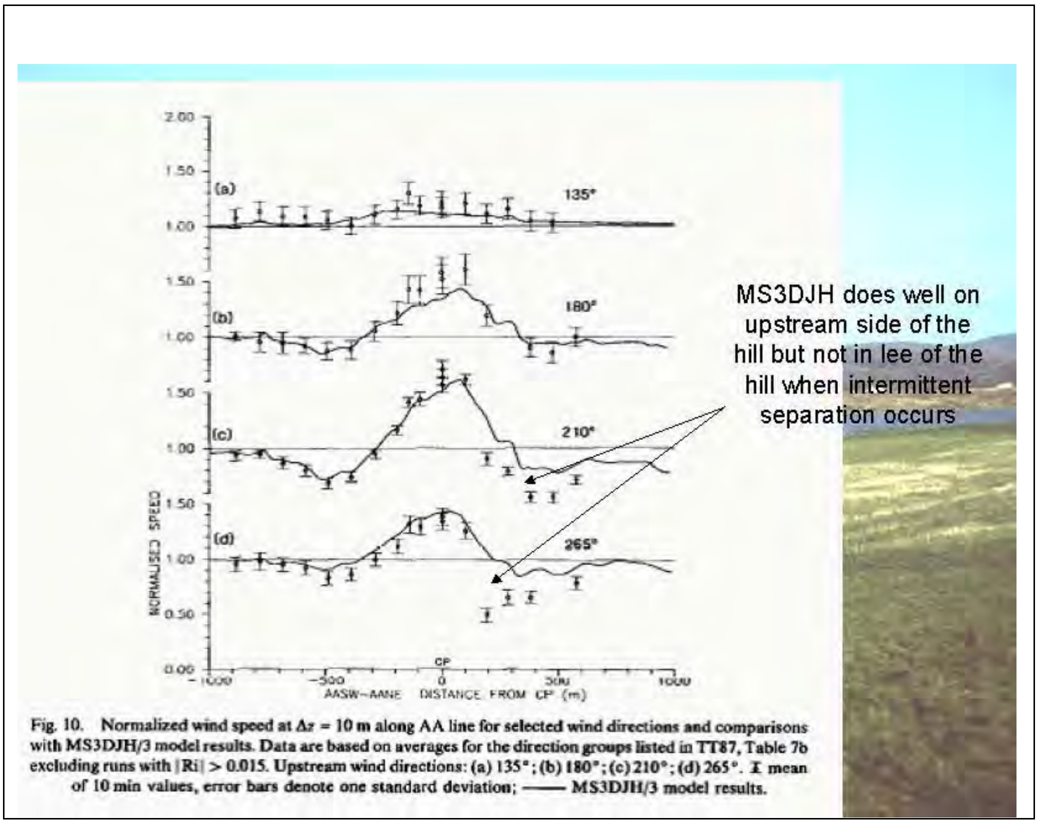


Fig. 10. Normalized wind speed at Δz = 10 m along AA line for selected wind directions and comparisons with MS3DJH/3 model results. Data are based on averages for the direction groups listed in TT87, Table 7b excluding runs with |Ri| > 0.015. Upstream wind directions: (a) 135°; (b) 180°; (c) 210°; (d) 265°. I mean of 10 min values, error bars denote one standard deviation; —— MS3DJH/3 model results.

Simple Guidelines estimates, GLW: A=3.5 - 4, B=1.8 - 1.6

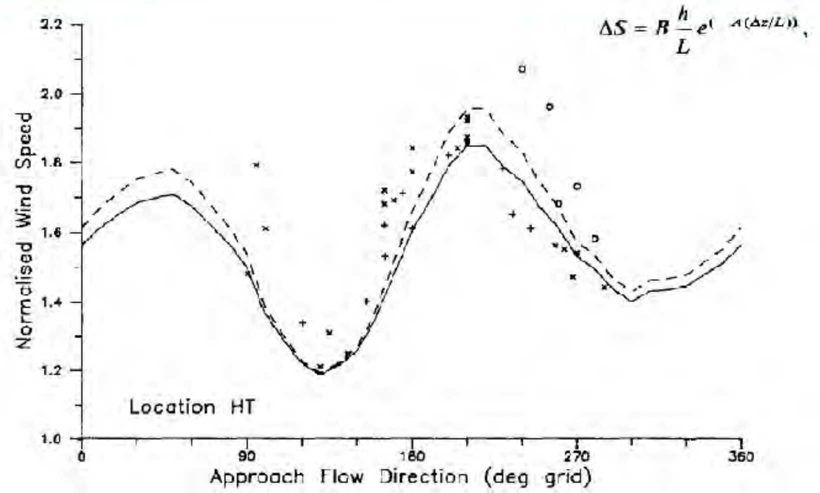


Fig. 2. Normalized wind speeds at HT as a function of φ, the wind direction at RS: —— guidelines estimate, Δz = 10 m; ---- guidelines estimate, Δz = 3 m; + Askervein '82 runs, Δz = 10 m; × Askervein '83 runs, Δz = 10 m; ○ Askervein '83 runs, Δz = 3 m.

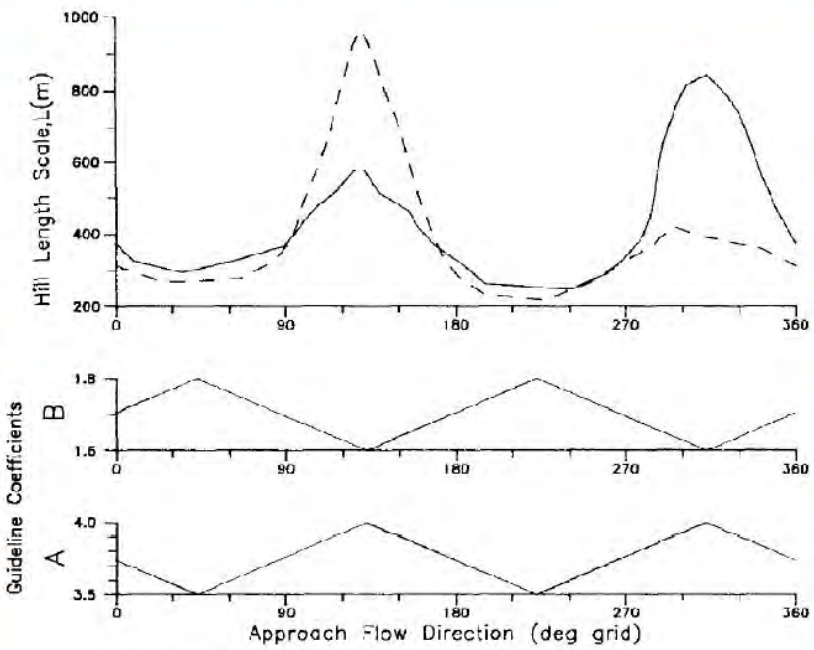
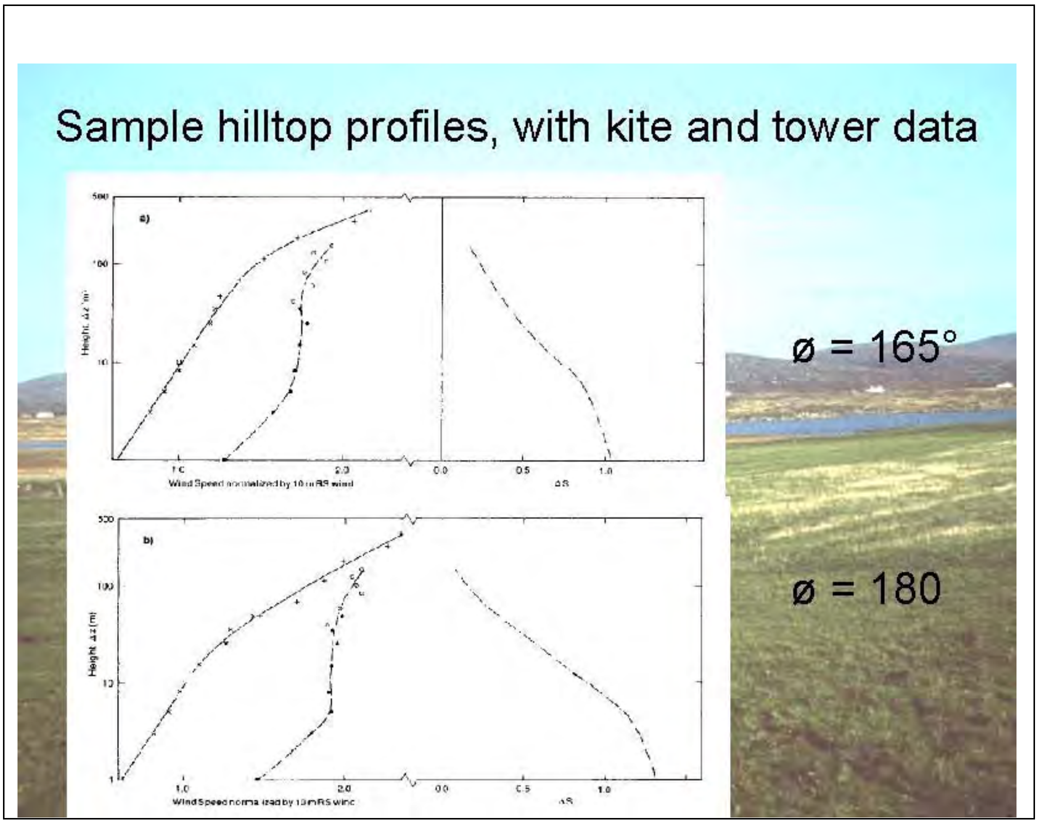


Fig. 4. L, A, and B as functions of direction: —— HT; ---- CP.



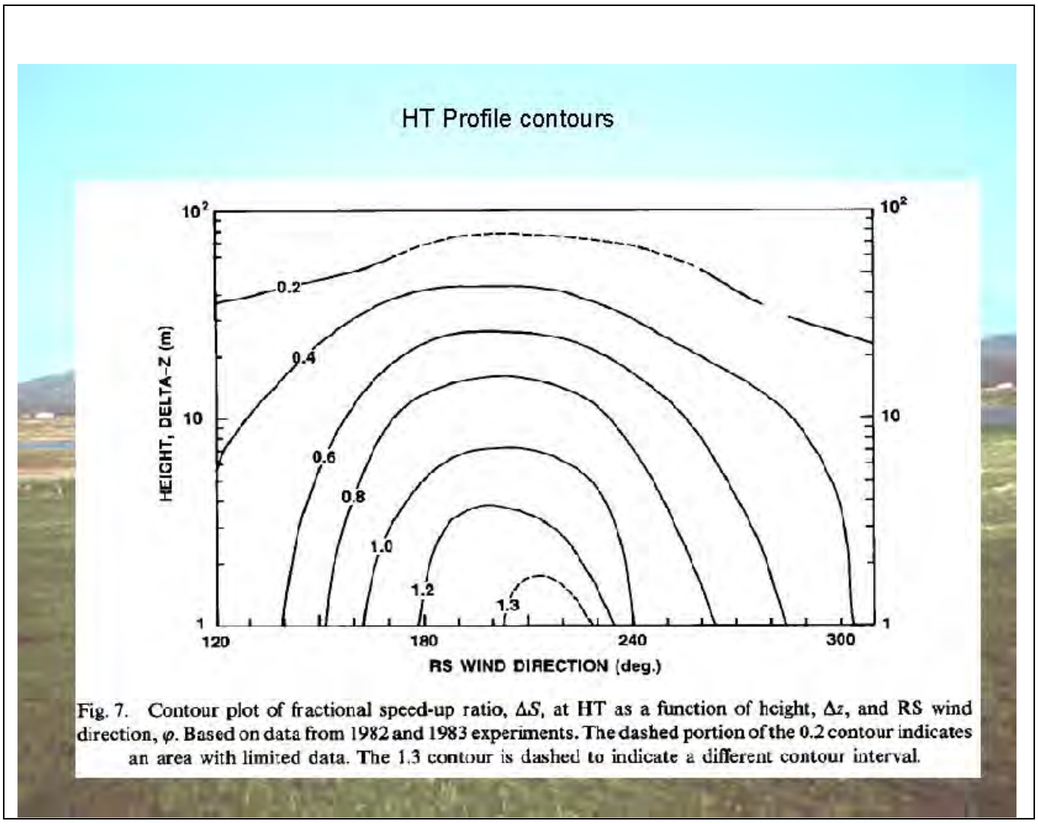


Fig. 7. Contour plot of fractional speed-up ratio, ΔS, at HT as a function of height, Δz, and RS wind direction, φ. Based on data from 1982 and 1983 experiments. The dashed portion of the 0.2 contour indicates an area with limited data. The 1.3 contour is dashed to indicate a different contour interval.

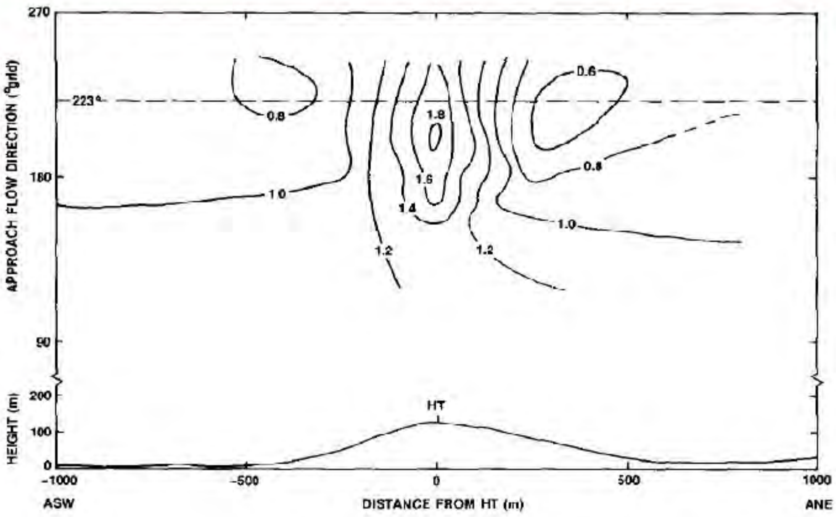


Fig. 7. Contour plot of normalized wind speed at Δz = 10 m along A line for different wind directions, Askervein '82. Topographic cross-section also shown. Run 1.23a (low wind speed) and 2.29a (direction change during the run) have been excluded.

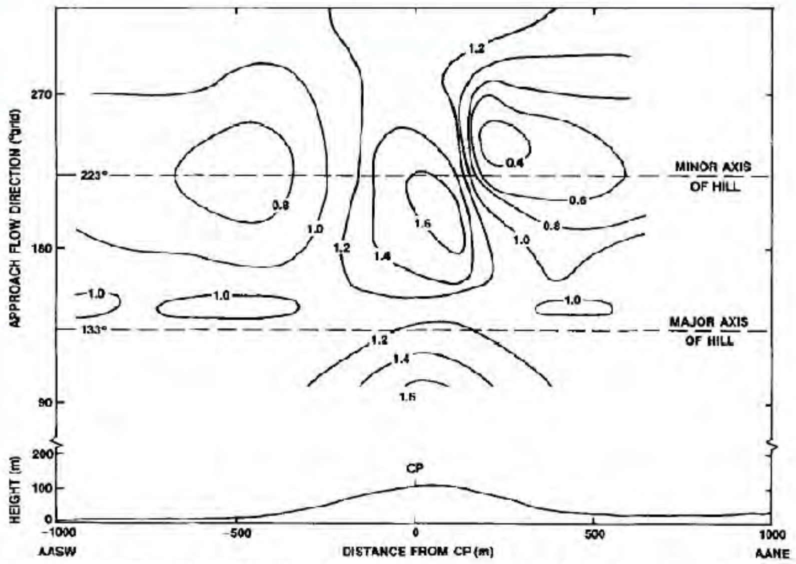


Fig. 12. Contour plots of normalized wind speed data at Δz = 10 m along AA line for different wind directions, Askervein '83. Data based on averages for the directional groups.

Sample turbulence statistics, RS + upwind hill foot

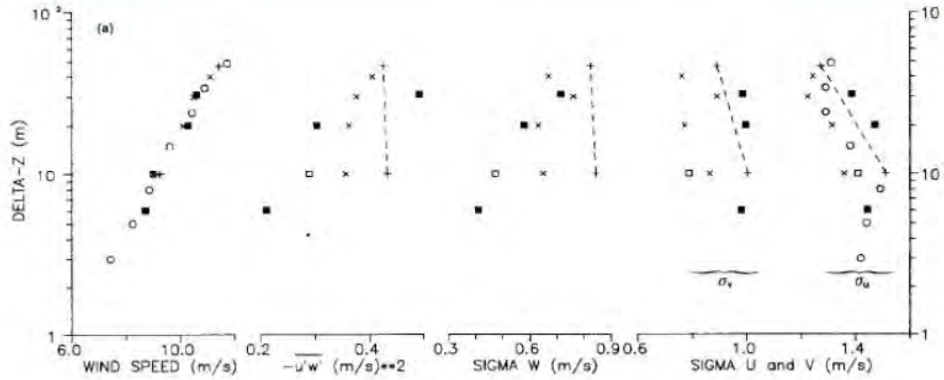
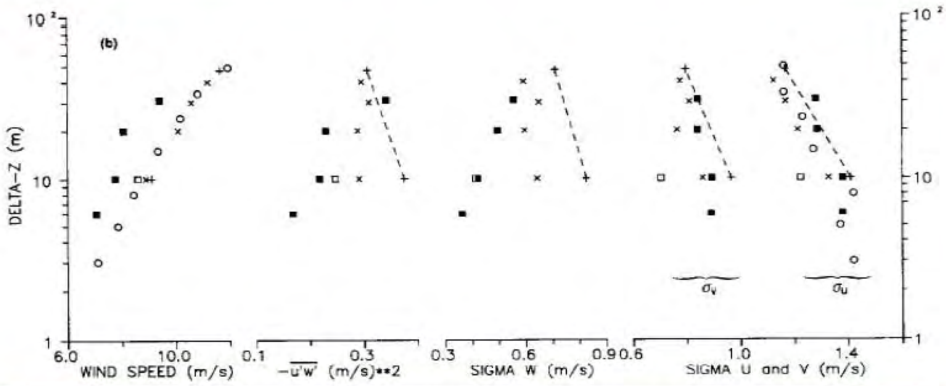


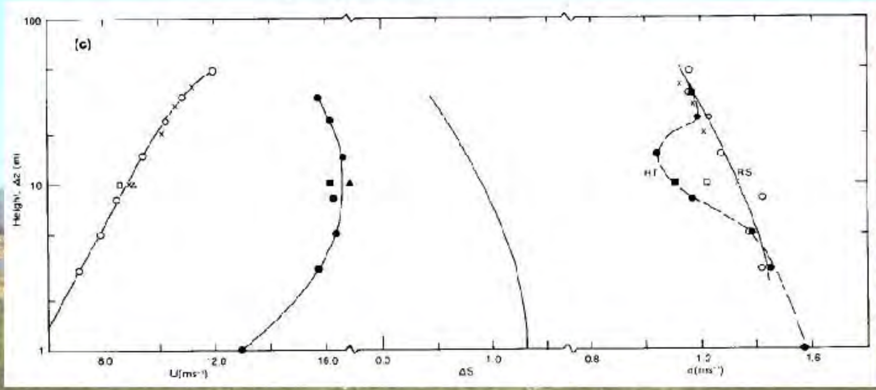
Fig. 4a.

Fig. 4. Profiles of wind speed and integral turbulence statistics at RS and ASW60. (a) Run TU01-B, $\varphi = 180°$. (b) Run TU03-B, $\varphi = 210°$.
RS data: ○ Cup anemometers; + Sonic anemometers; × Tilted Gill UVW anemometers; □ Vertical Gill UVW (10 m). ASW60 data: ■ Vertical Gill UVW.

ø = 210 , note blocking at ASW 60



Hilltop (HT) turbulence



Flow from 210 degrees, normal to ridge, σ is based on cup anemometer variance and 3-cpt Gill at 10m.

The main limitation of the Askervein dataset at the time of writing is the lack of more extensive published turbulence data for hilltop locations. Work is presently in hand at Risø to rectify this limitation. It would be interesting to run a third experiment at the site to obtain additional turbulence data, and perhaps to add surface pressure measurements.

From WT 95

Hilltop (HT) turbulence

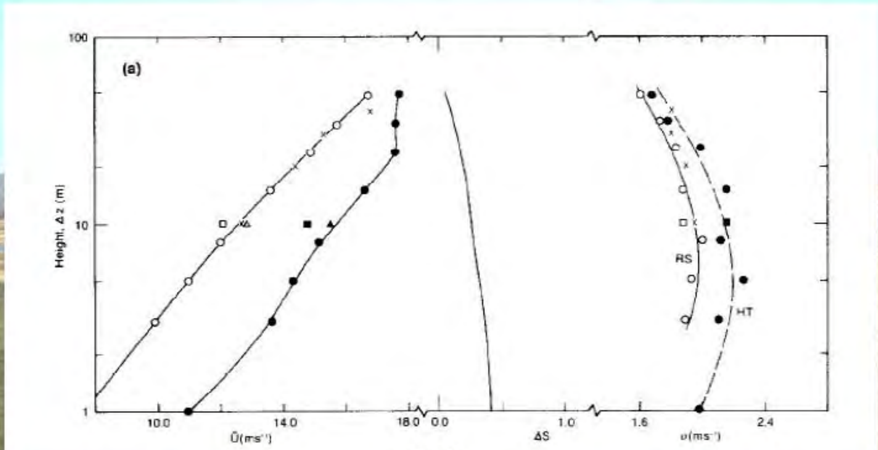


Fig. 6a.

Flow from 130 degrees, approximately parallel to ridge, σ is based on cup anemometer variance and 3-cpt Gill at 10m

Inner Layer Depths

The formulae to be considered (**JH**, **JEN** and **CL**, respectively) are:

$$(\ell/L)\ln(\ell/z_0) = 2\kappa^2,$$

$$(\ell/L)\ln^2(\ell/z_0) = 2\kappa^2,$$

$$(\ell/L)\ln(\ell/z_0) = \text{constant}.$$

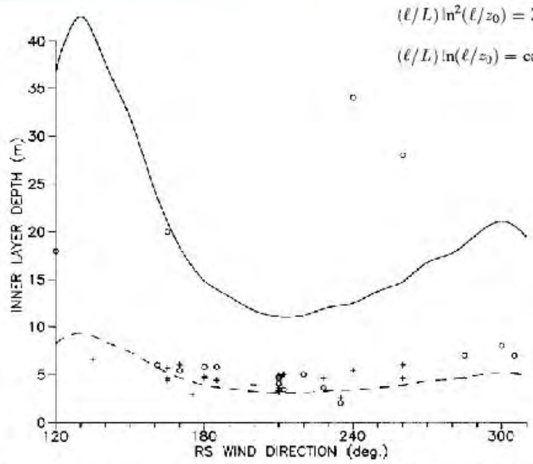


Fig. 8. Estimates and observations of inner-layer depth as functions of wind direction. Askervein hilltop (HT). + observed height of ΔU_{max}; ○ observed height at which $\Delta\sigma_u = 0$; —— Jackson–Hunt estimate (TT87, equation (4)); - - - - - Jensen estimate (TT87, Equation (55)).

The roughness length anomaly

Table 3.7: Profile-derived z_0 and u_* values at CP and BSE10 during selected MF runs, Oct. 7–10, 1983.*

Run	CP z_0(m)	CP u_*(ms^{-1})	BSE 10 z_0(m)	BSE 10 u_*(ms^{-1})
MF07-A	0.0003	0.43	.0011	0.55
MF07-D	–	–	.0010	0.68
MF08	–	–	.0009	0.53
MF09-A	0.0012	0.64	.0006	0.58
MF09-B	0.0017	0.65	.0013	0.60
MF09-C	0.0007	0.56	.0009	0.59
MF10-A	0.0006	0.54	.0011	0.62
MF10-B	0.0007	0.53	.0008	0.56

Based on winds measured at 0.5m and 3m levels.

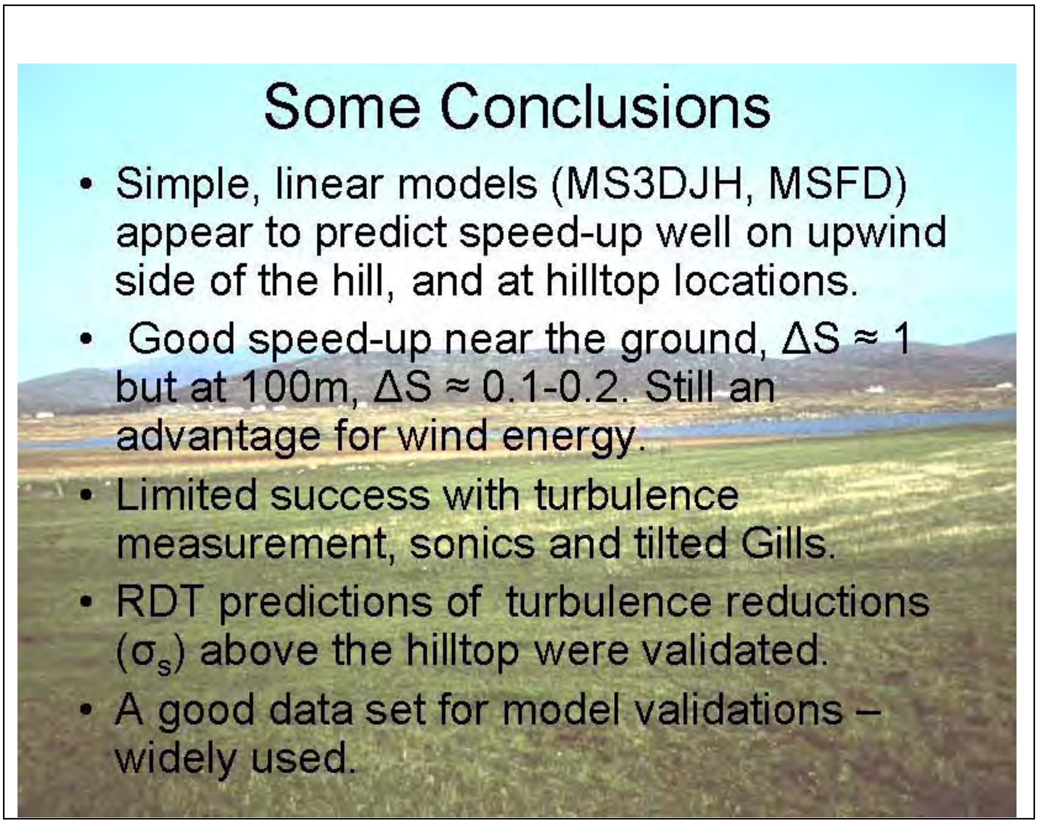
*see discussion in text with regard to the interpretation of these values

(2)

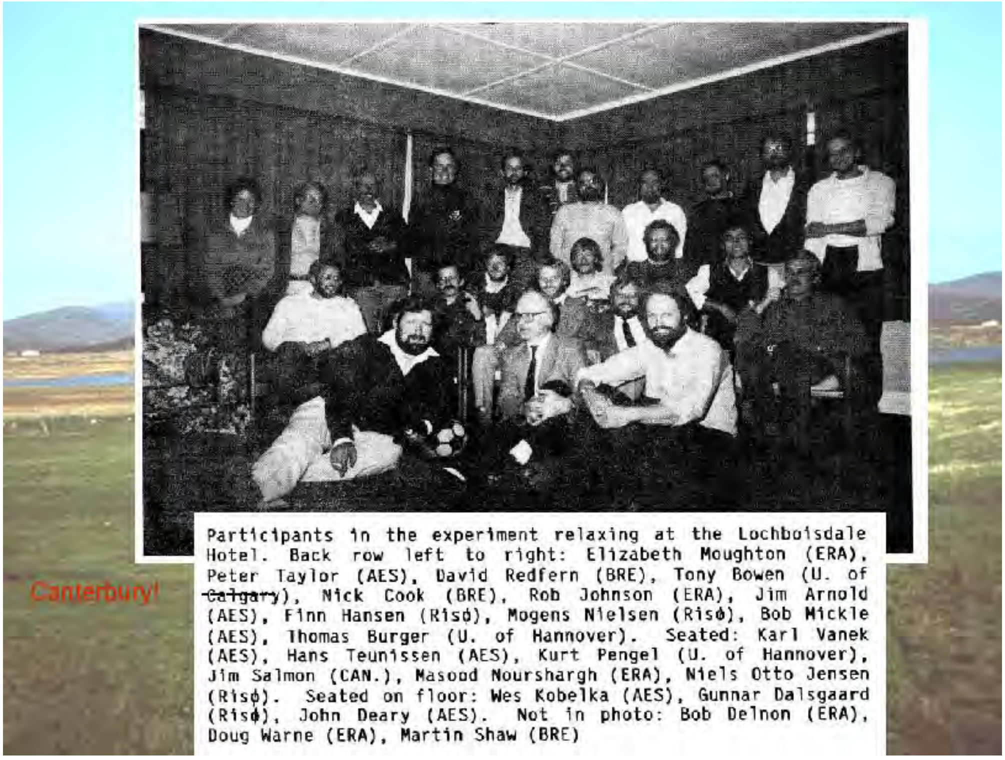
RS PROFILE DATA

u_*, ms^{-1}	z_0, m
0.37	0.024
0.49	0.026
0.54	0.030
0.85	0.028
0.63	0.023
0.55	0.013
0.49	0.022
0.49	0.017
0.69	0.029
0.63	0.022
0.57	0.020
0.64	0.020
0.51	0.014
0.45	0.009
0.38	0.039
0.75	0.021
0.64	0.024
0.63	0.027
0.66	0.022

Note : Hilltop area appears rougher than z_0 = 1 mm.
Should look at other ways to estimate z_0 and u_*


Some Conclusions
• Simple, linear models (MS3DJH, MSFD) appear to predict speed-up well on upwind side of the hill, and at hilltop locations.
• Good speed-up near the ground, ΔS ≈ 1 but at 100m, ΔS ≈ 0.1-0.2. Still an advantage for wind energy.
• Limited success with turbulence measurement, sonics and tilted Gills.
• RDT predictions of turbulence reductions (σ_s) above the hilltop were validated.
• A good data set for model validations – widely used.


Acknowledgements
• All participants in the experiment (next slide), plus those who have used the data.
• Various funding agencies, then and now, IEA for support of the project.
• Environment Canada (formerly AES)
• Risø National Laboratories (Denmark)
• University of Hannover (Germany)
• ERA Technology Ltd (UK)
• Building Research Establishment (UK)
• University of Canterbury (New Zealand)


Participants in the experiment relaxing at the Lochboisdale Hotel. Back row left to right: Elizabeth Moughton (ERA), Peter Taylor (AES), David Redfern (BRE), Tony Bowen (U. of ~~Calgary~~), Nick Cook (BRE), Rob Johnson (ERA), Jim Arnold (AES), Finn Hansen (Risø), Mogens Nielsen (Risø), Bob Mickle (AES), Thomas Burger (U. of Hannover). Seated: Karl Vanek (AES), Hans Teunissen (AES), Kurt Pengel (U. of Hannover), Jim Salmon (CAN.), Masood Nourshargh (ERA), Niels Otto Jensen (Risø). Seated on floor: Wes Kobelka (AES), Gunnar Dalsgaard (Risø), John Deary (AES). Not in photo: Bob Delnon (ERA), Doug Warne (ERA), Martin Shaw (BRE)
Canterbury!

“The Bolund Experiment” - by J. Berg, J. Mann and H.E. Jørgensen

The Bolund Experiment

Andreas Bechmann, **Jacob Berg**, Mike Courtney, **Hans E. Jørgensen**, **Jakob Mann**, Niels N. Sørensen
in cooperation with Vestas

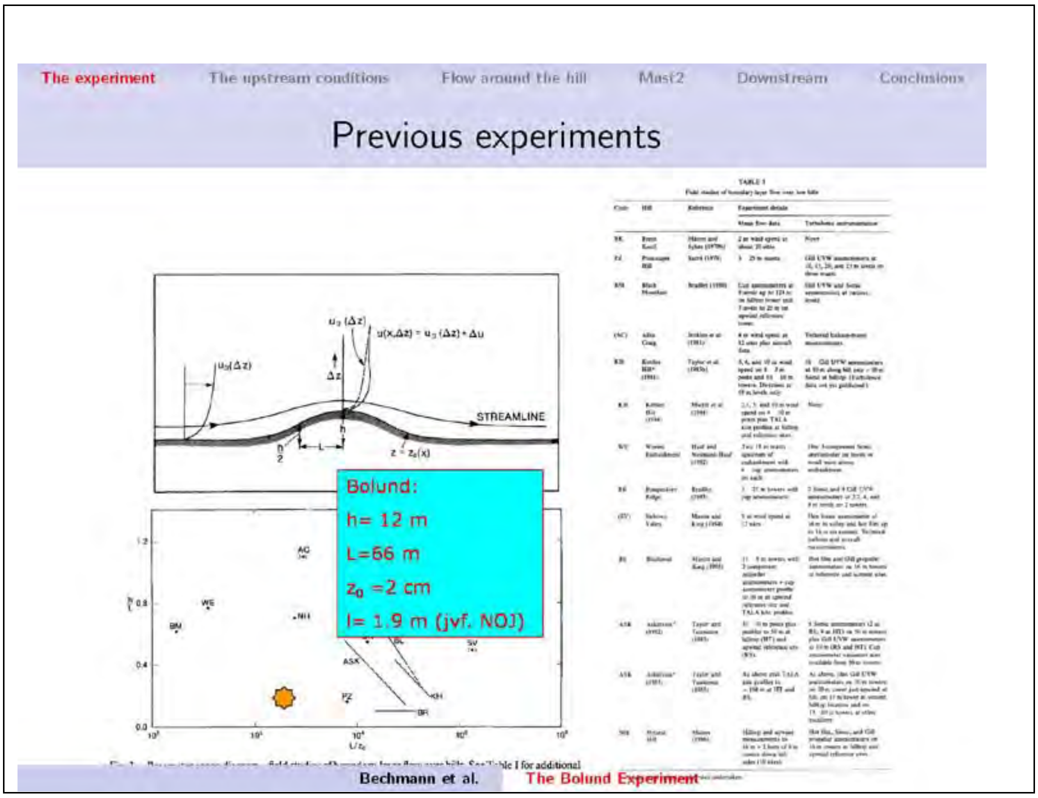
Risø DTU, Roskilde, Denmark

December 3-4, 2009 – Bolund Workshop, Risø DTU, Denmark

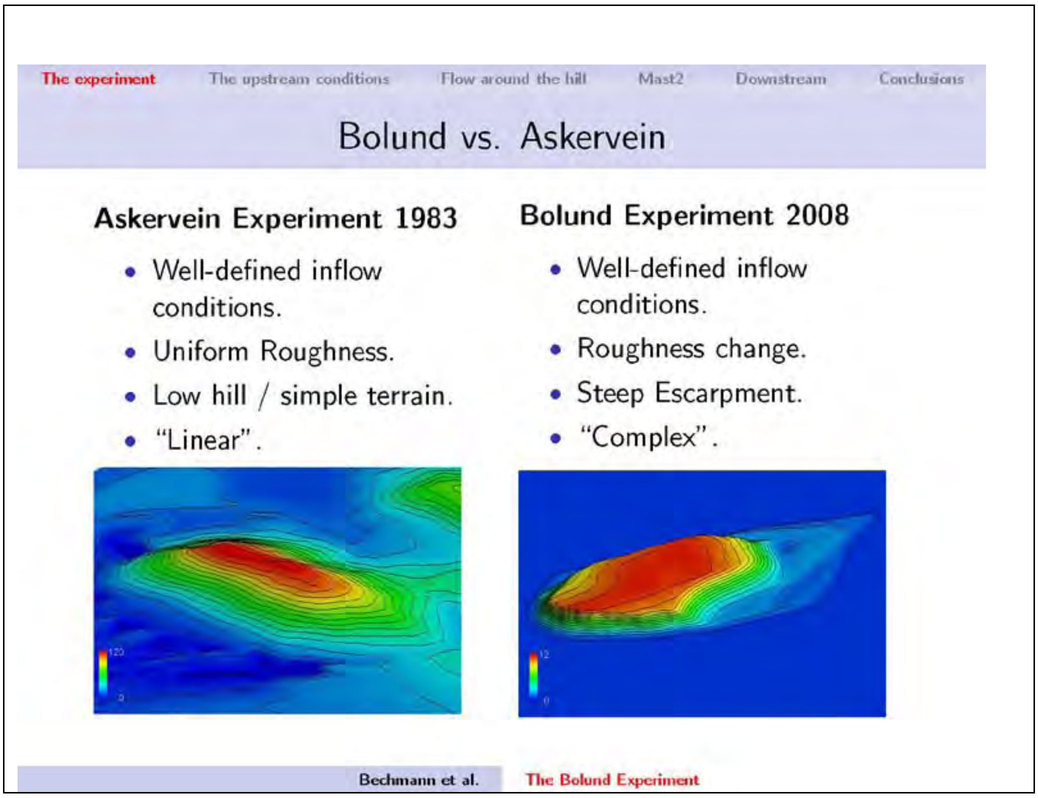
Approvals needed for the Bolund experiment

- Landowners' approval (Karen, Christian and Benny)
- Fredningsnævnet
- Building approval (Byggesagsgodkendelse, Roskilde Kommune)
- Environmental Center Roskilde
- Neighbor hearing (two complaints filed)
- Meeting with the neighbors (a very peaceful meeting with some understanding)
- Danish Maritime Safety Administration (Farvandsdirektoratet in Thisted)

Normal processing time 1/2 year - Bolund $\sim$ 3 months



The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Previous experiments
STREAMLINE
Bolund:
h= 12 m
L=66 m
z_0 =2 cm
l= 1.9 m (jvf. NOJ)
Bechmann et al.
The Bolund Experiment



The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Bolund vs. Askervein
Askervein Experiment 1983
• Well-defined inflow conditions.
• Uniform Roughness.
• Low hill / simple terrain.
• "Linear".
Bolund Experiment 2008
• Well-defined inflow conditions.
• Roughness change.
• Steep Escarpment.
• "Complex".
Bechmann et al.
The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

The Bolund peninsula

Map width: 50 km

Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

The Bolund peninsula

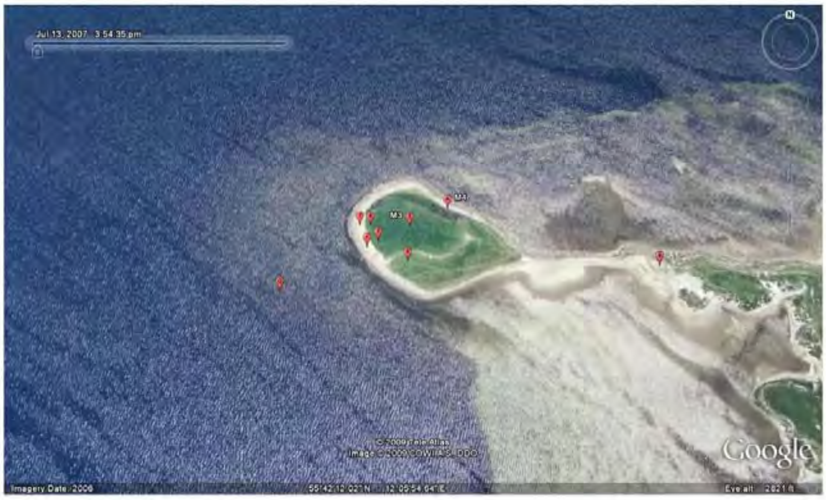
Map width: 7 km

Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

The Bolund peninsula

Map width: 1 km

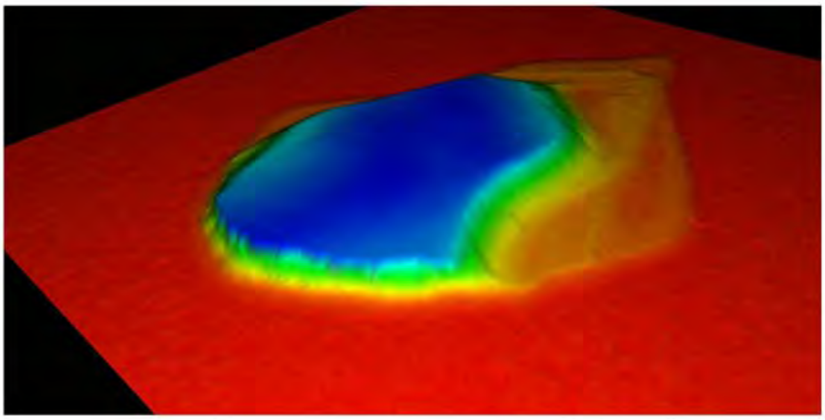


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Height scanning with laser

Optech Airborne Laser Terrain Mapper: ≈ 2 m resolution

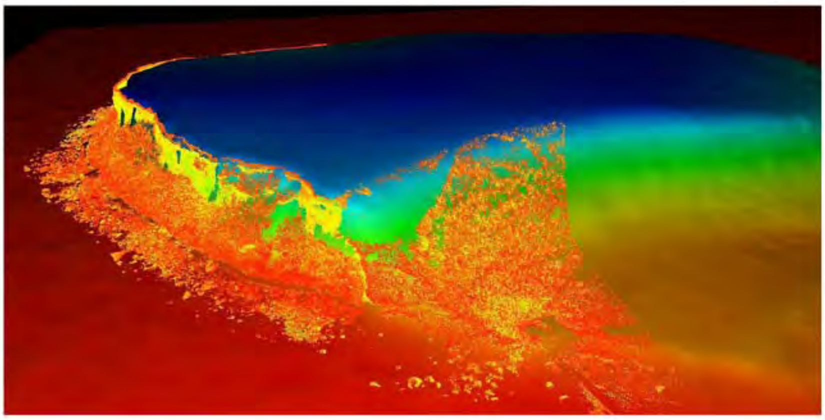


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied

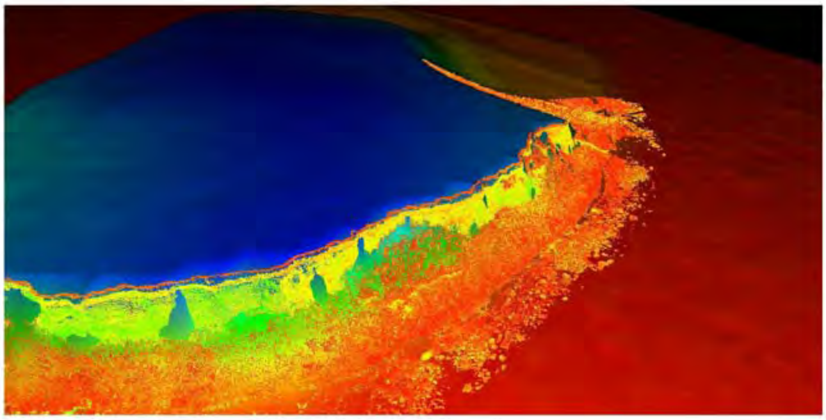


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied

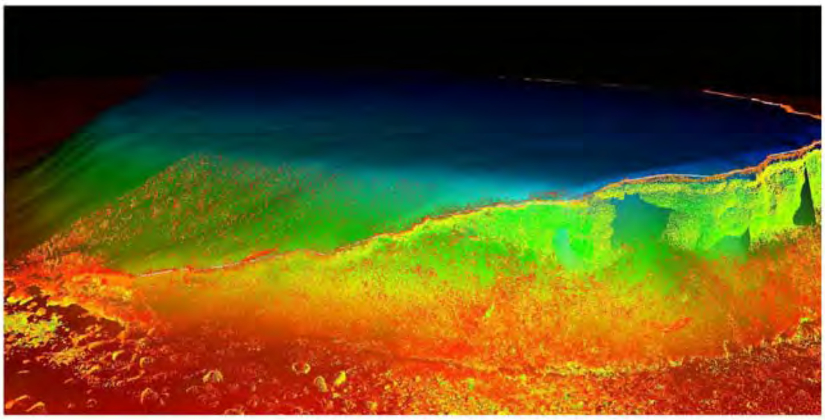


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Height scanning with laser

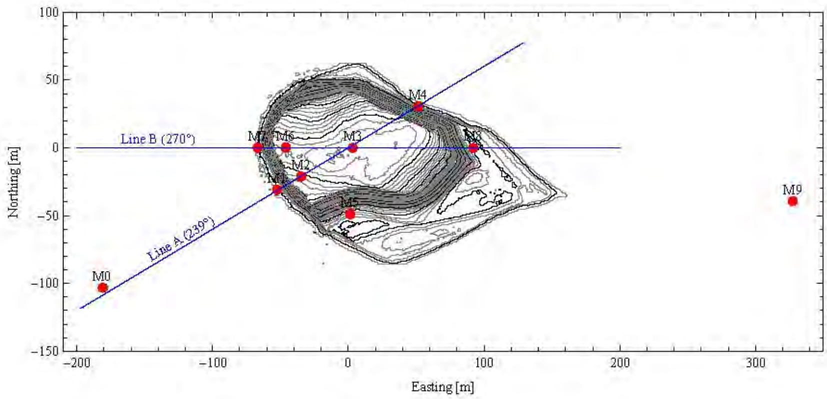
Cliff to steep: additional < 0.1 m resolution scanning applied



Bechmann et al. | The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Masts



Bechmann et al. | The Bolund Experiment

Erection of masts

Instrumentation

- 23 Metek USA-1 Basic sonics – off-line flow correction
- 12 Risø cup anemometers (WindSensor P2546)
- 2 ZephIR lidars + one scanning lidar
- Temperature and temperature difference
- No pressure and no humidity

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Sonic Configuration

Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

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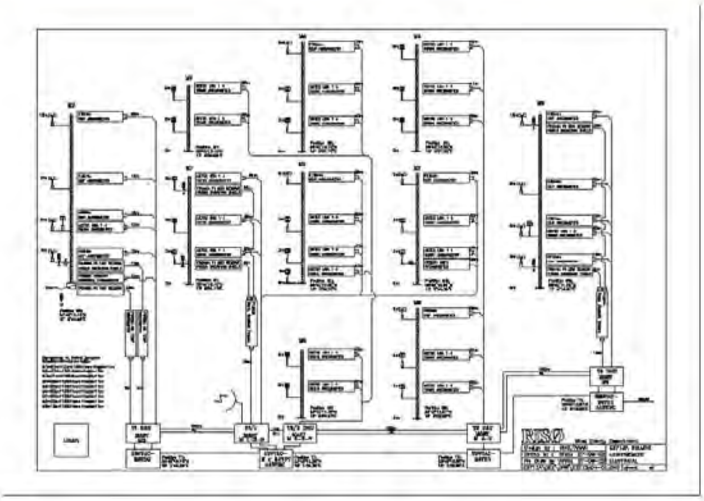
The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Technical Diagram

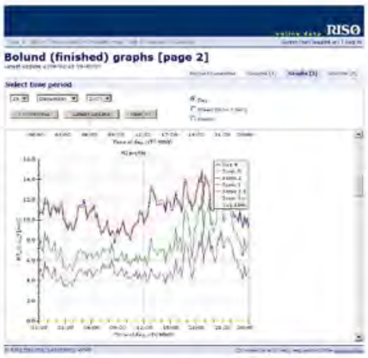


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Database and Rodeo

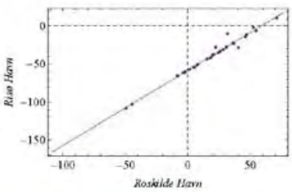
- Central Acquisition of all Meteorological Data (20 Hz)
- Direct Data Transfer to Risø via RadioLink
- Database Storage MySQL (20 Hz and 10 min averages)
- Online Data Display

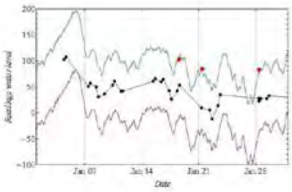


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Water level in Roskilde Fjord

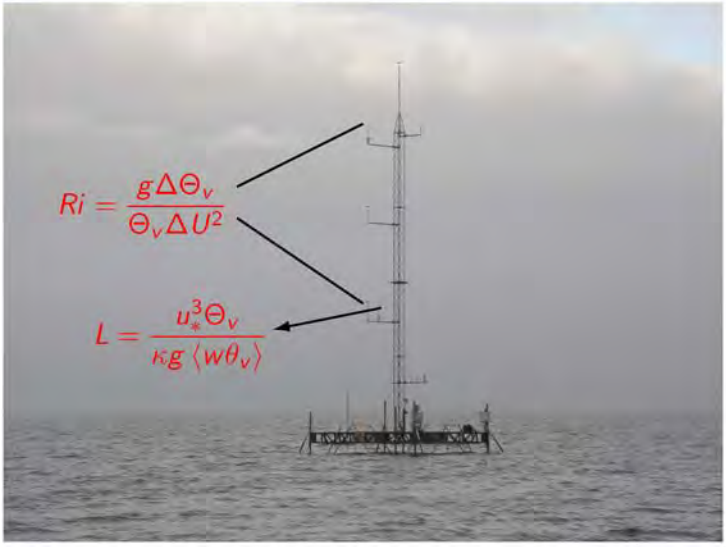




Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

The upstream mast M0: Atmospheric stability



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The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Fetch

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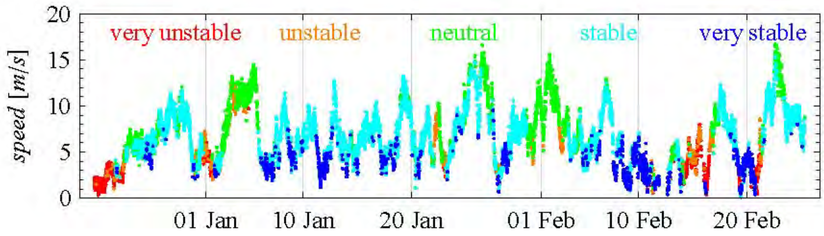
The experiment The upstream conditions Flow around the hill Mast2 Downstream Conclusions

Measurement period and stability



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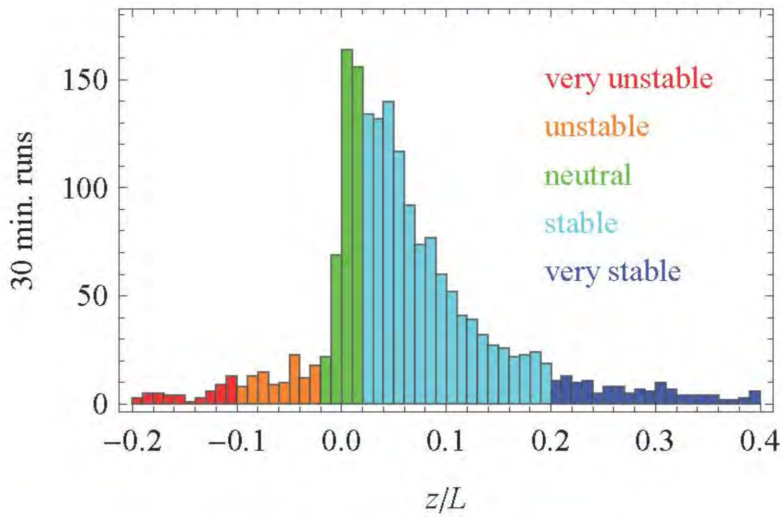
The experiment The upstream conditions Flow around the hill Mast2 Downstream Conclusions

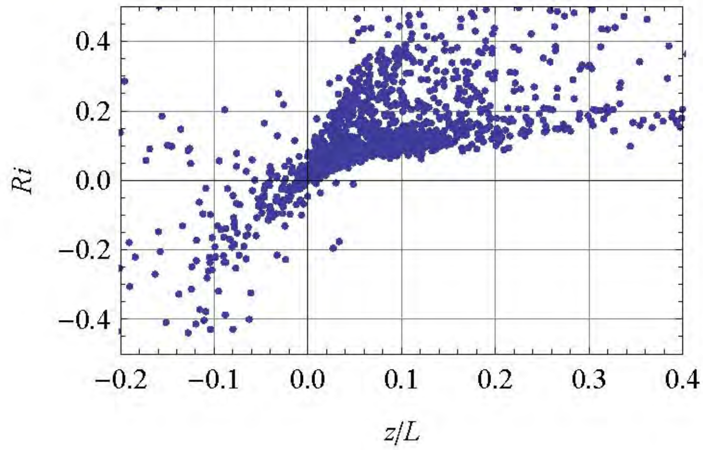
Stability in terms of the Monin-Obukhov stability parameter z/L



Bechmann et al. The Bolund Experiment

Atmospheric stability: z/L versus Ri

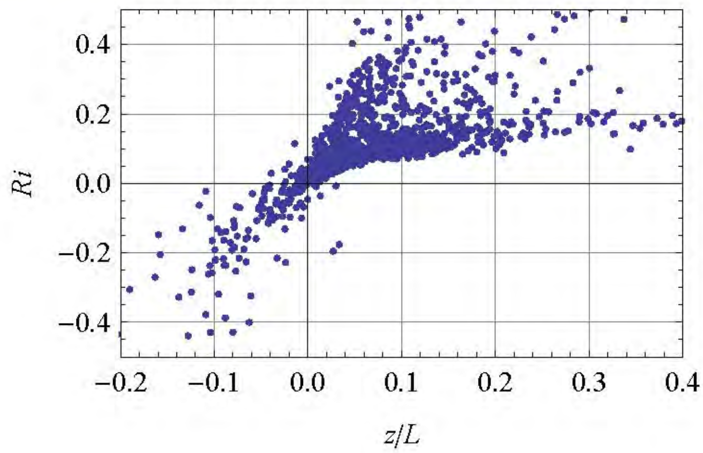
$180^\circ < \theta < 360^\circ$ and $U_5 > 0$ m/s



The experiment The upstream conditions Flow around the hill Mast2 Downstream Conclusions

Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 4$ m/s

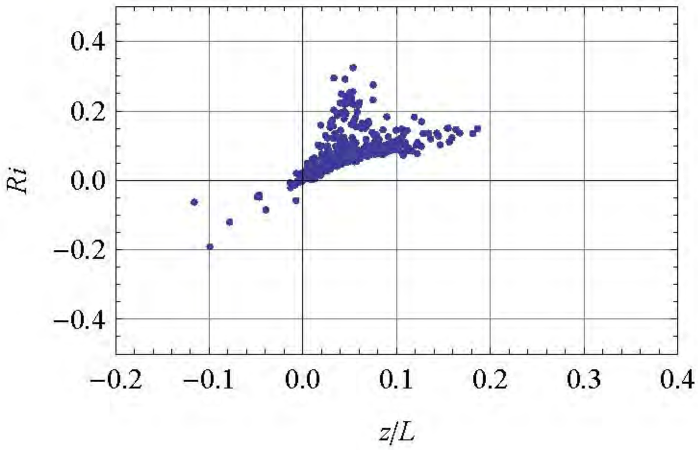


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 8$ m/s

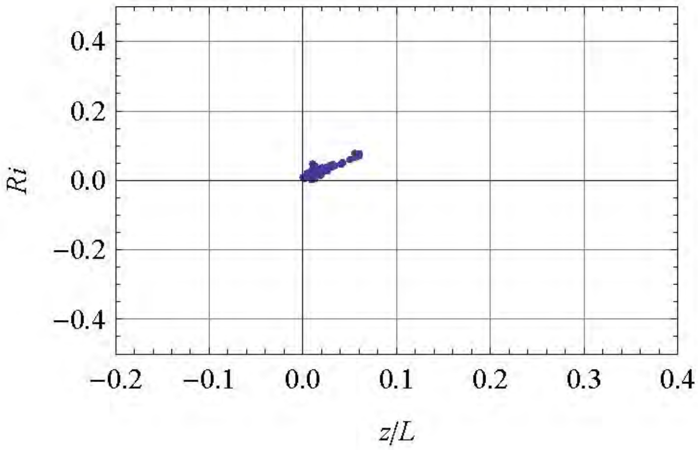


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 12$ m/s

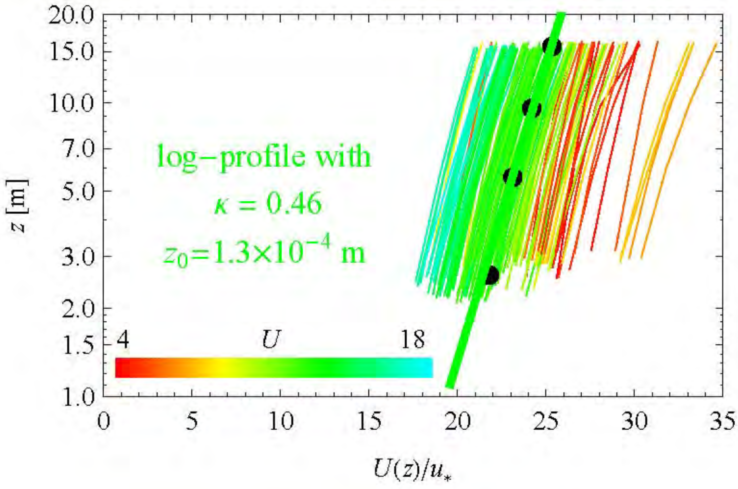


Bechmann et al. The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Neutral upwind profile

$-0.02 < z/L < 0.02$ and $260° < \theta < 300°$ (long fetch)

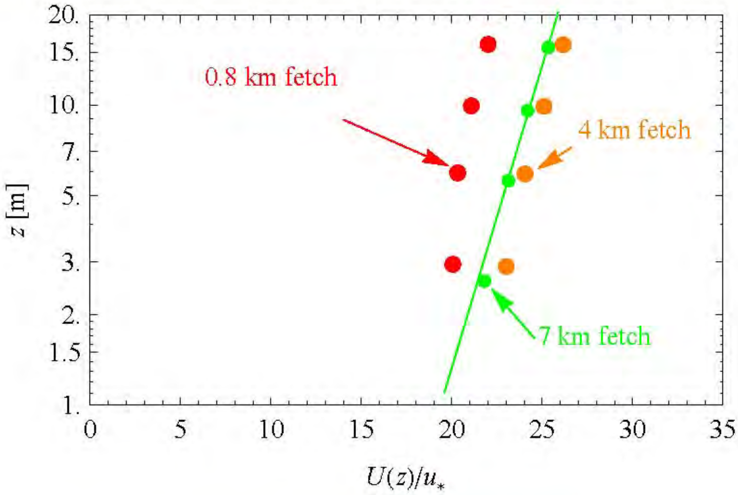


Bechmann et al. The Bolund Experiment

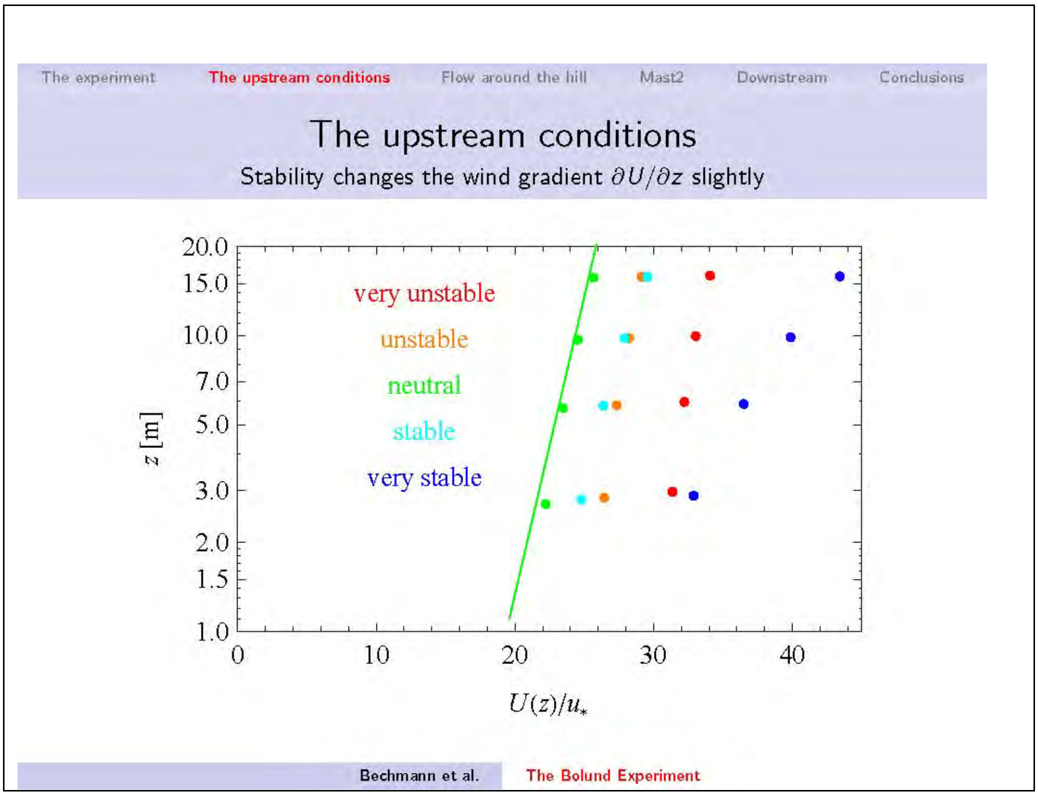
The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

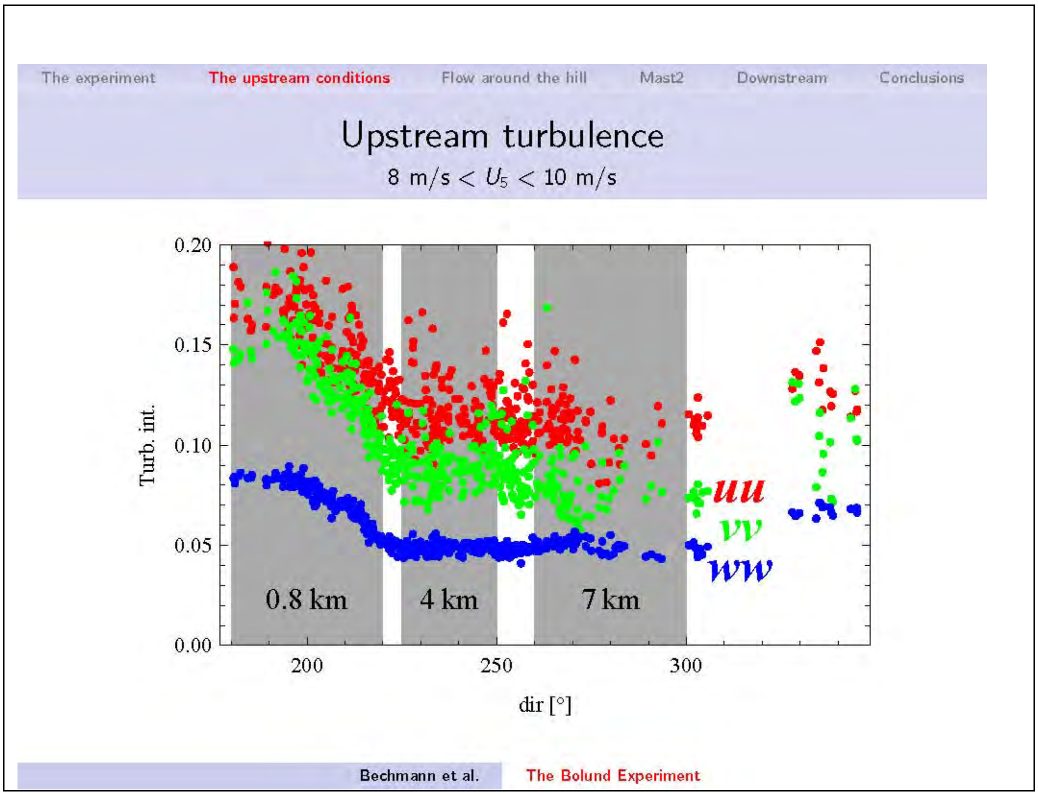
The upstream conditions

Is the flow "undisturbed"? ($-0.02 < z/L < 0.02$)



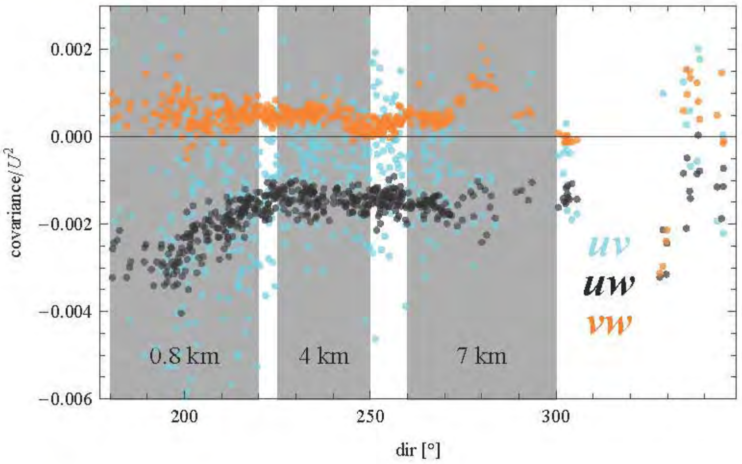
Bechmann et al. The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
The upstream conditions
Stability changes the wind gradient $\partial U/\partial z$ slightly
very unstable
unstable
neutral
stable
very stable
20.0
15.0
10.0
7.0
5.0
3.0
2.0
1.5
1.0
z [m]
0
10
20
30
40
$U(z)/u_*$
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Upstream turbulence
8 m/s < U_5 < 10 m/s
0.20
0.15
0.10
0.05
0.00
Turb. int.
0.8 km
4 km
7 km
uu
vv
ww
200
250
300
dir [°]
Bechmann et al.
The Bolund Experiment

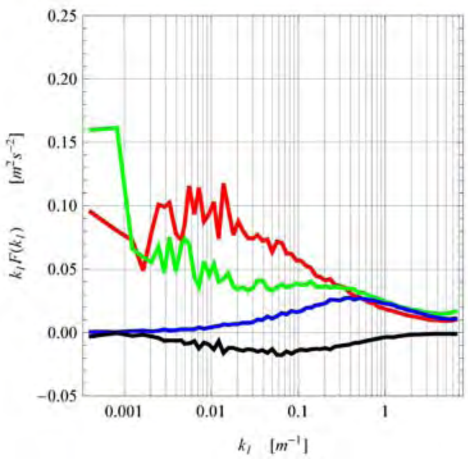
Upstream covariances

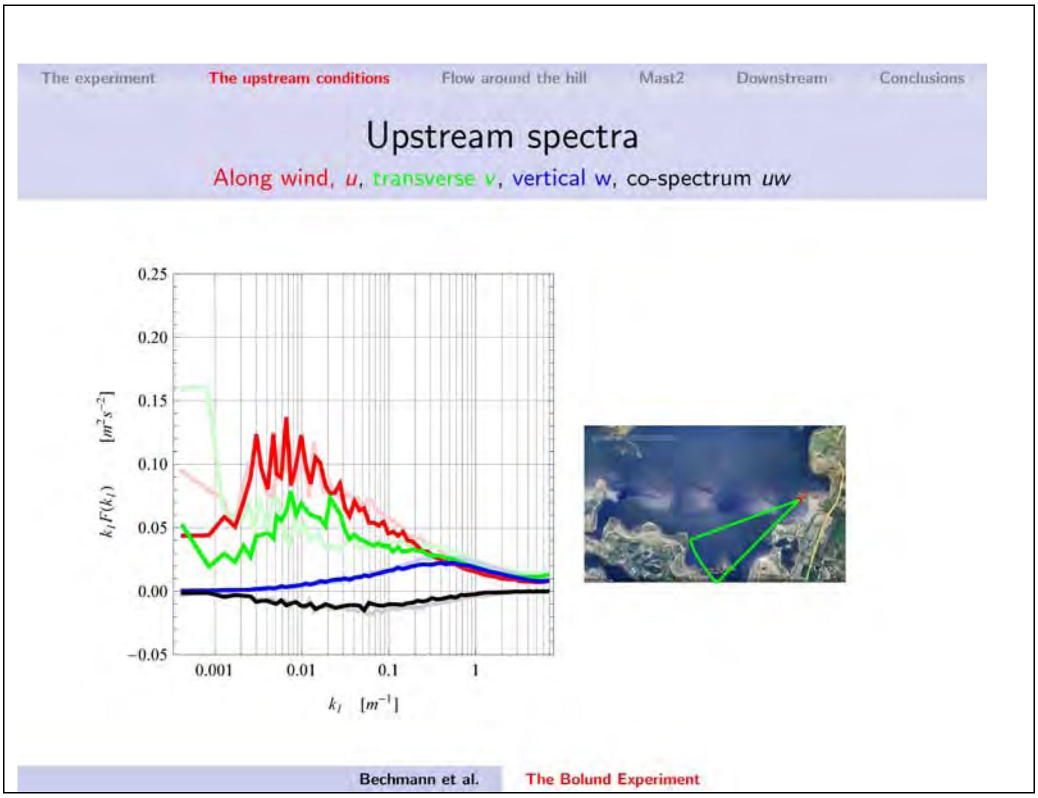
8 m/s < U_5 < 10 m/s



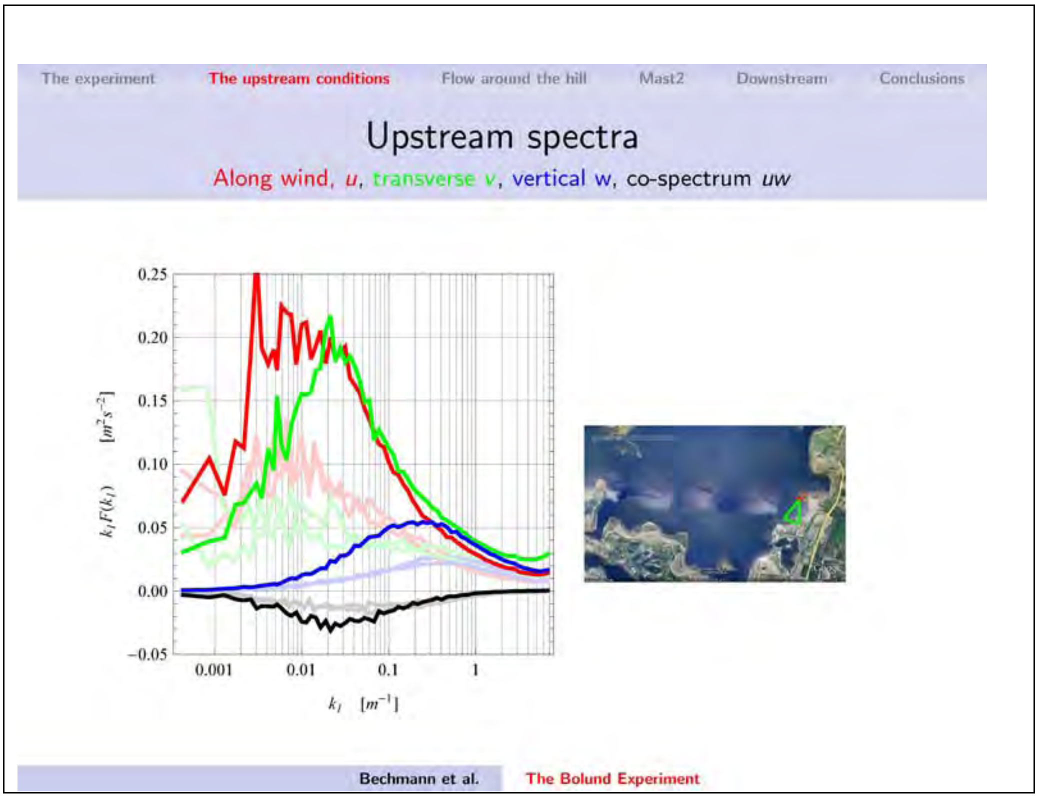
Upstream spectra

Along wind, *u*, transverse *v*, vertical w, co-spectrum *uw*

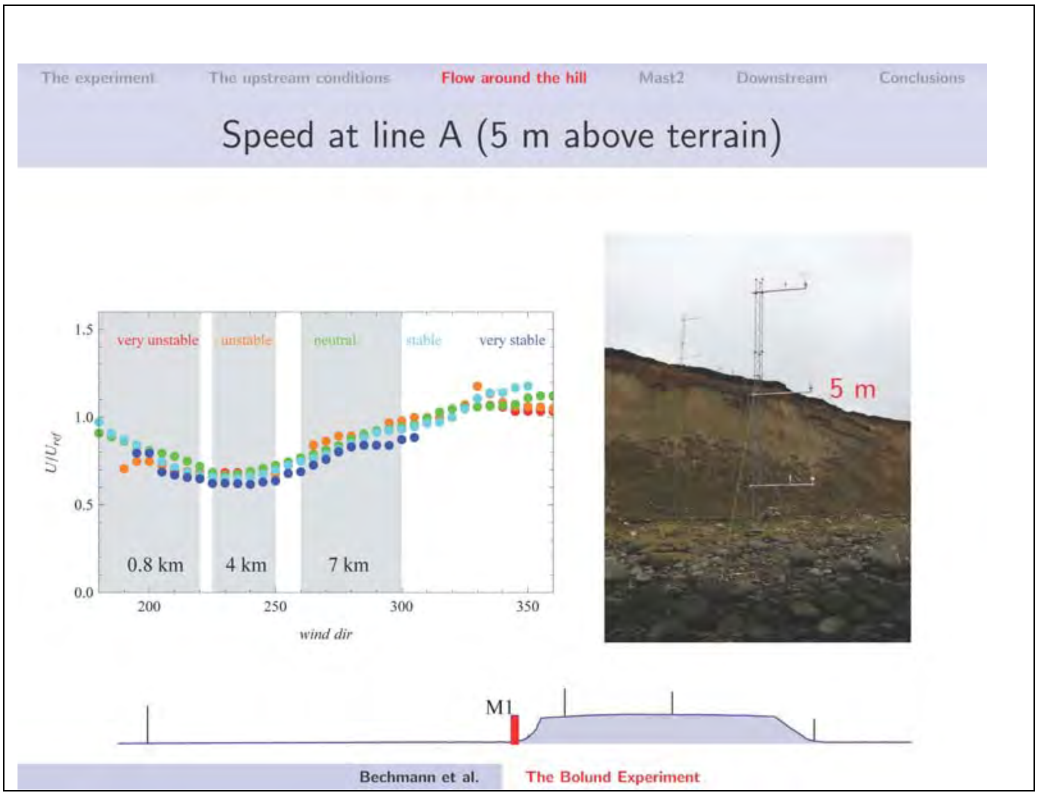




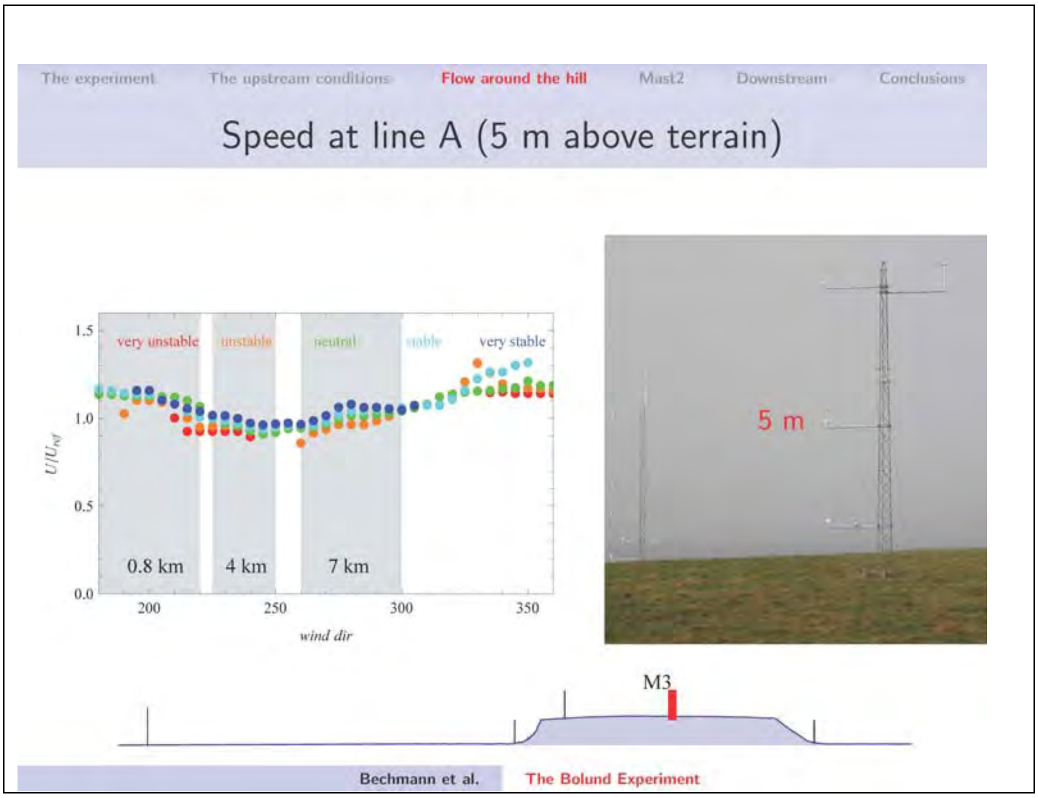
The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Upstream spectra
Along wind, u, transverse v, vertical w, co-spectrum uw
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
$k_1F(k_1)$ $[m^2s^{-2}]$
0.001
0.01
0.1
1
k_1 $[m^{-1}]$
Bechmann et al.
The Bolund Experiment



The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Upstream spectra
Along wind, u, transverse v, vertical w, co-spectrum uw
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
$k_1F(k_1)$ $[m^2s^{-2}]$
0.001
0.01
0.1
1
k_1 $[m^{-1}]$
Bechmann et al.
The Bolund Experiment

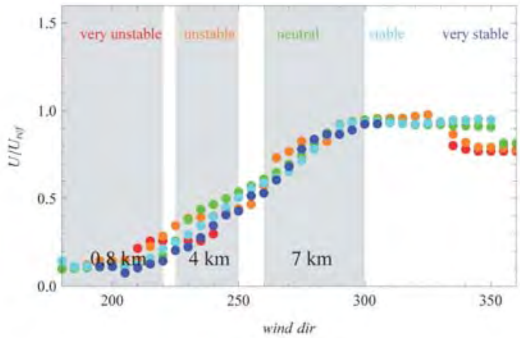


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Speed at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
1.5
1.0
0.5
0.0
U/U_{ref}
0.8 km
4 km
7 km
200
250
300
350
wind dir
5 m
M1
Bechmann et al.
The Bolund Experiment

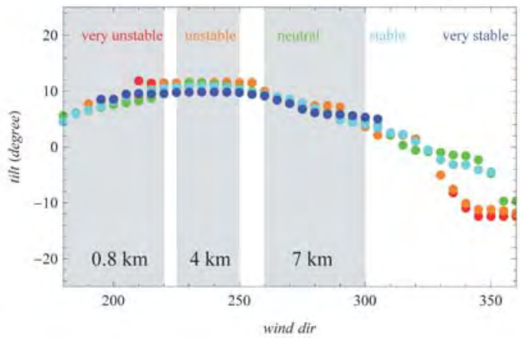


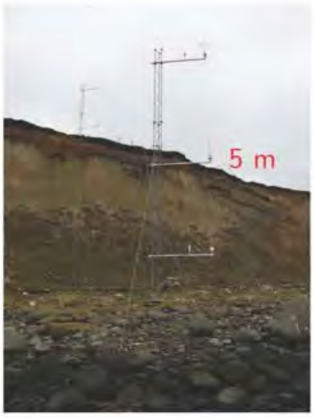
The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Speed at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
1.5
1.0
0.5
0.0
U/U_{ref}
0.8 km
4 km
7 km
200
250
300
350
wind dir
5 m
M3
Bechmann et al.
The Bolund Experiment

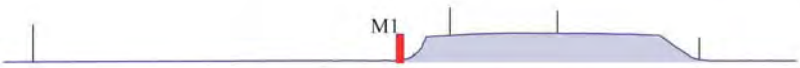
Speed at line A (5 m above terrain)



Tilt at line A (5 m above terrain)

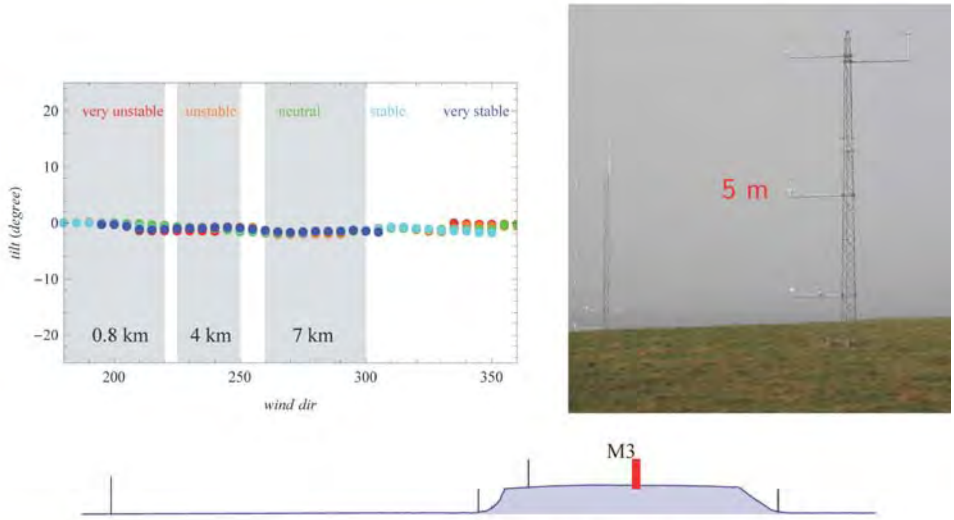






The experiment The upstream conditions **Flow around the hill** Mast2 Downstream Conclusions

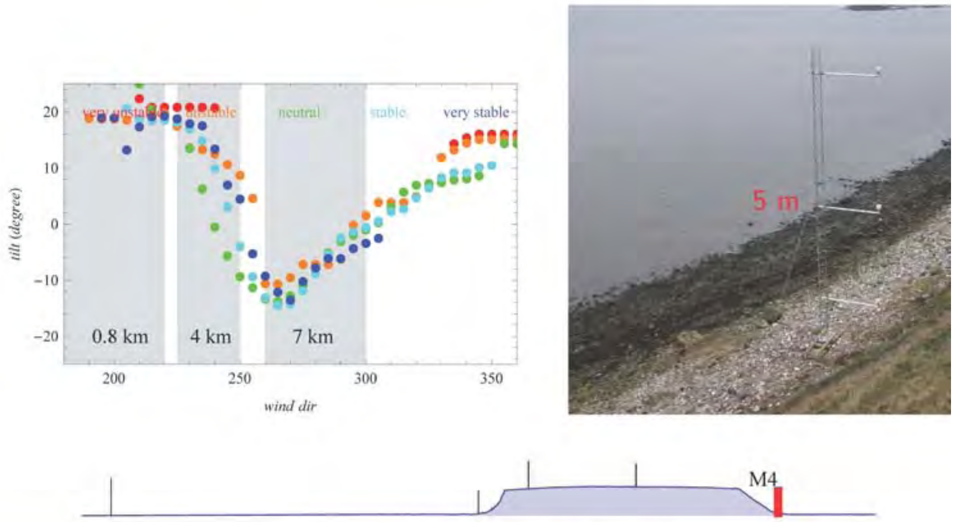
Tilt at line A (5 m above terrain)



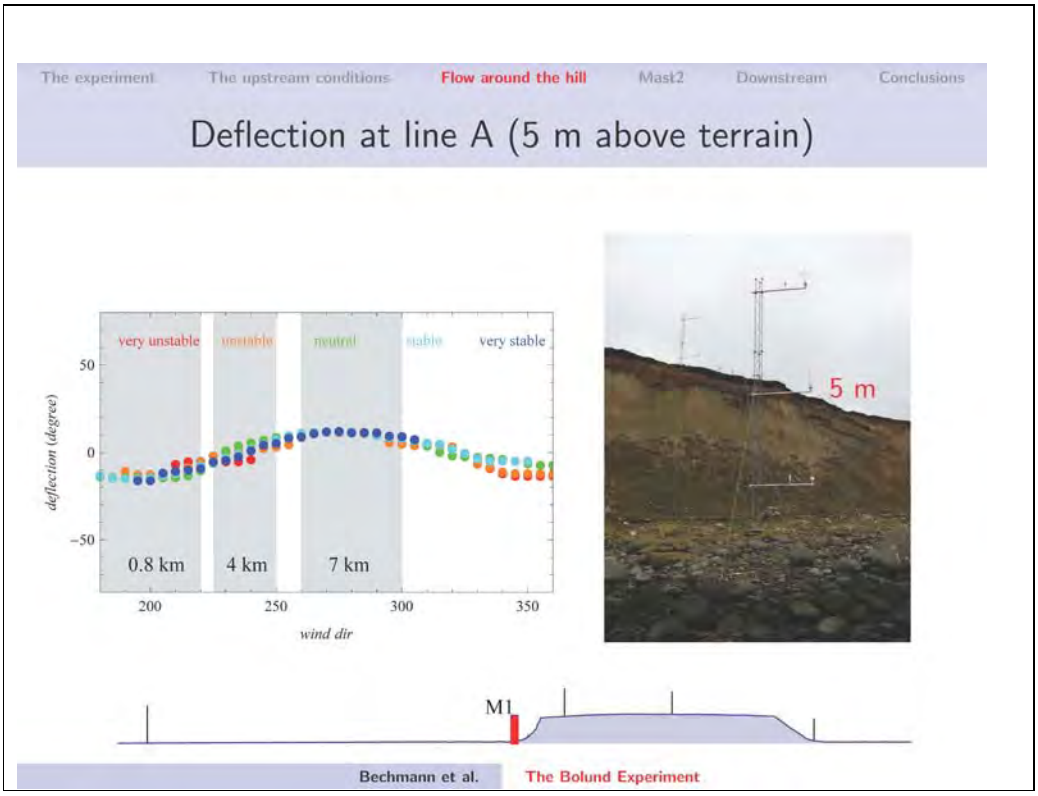
Bechmann et al. The Bolund Experiment

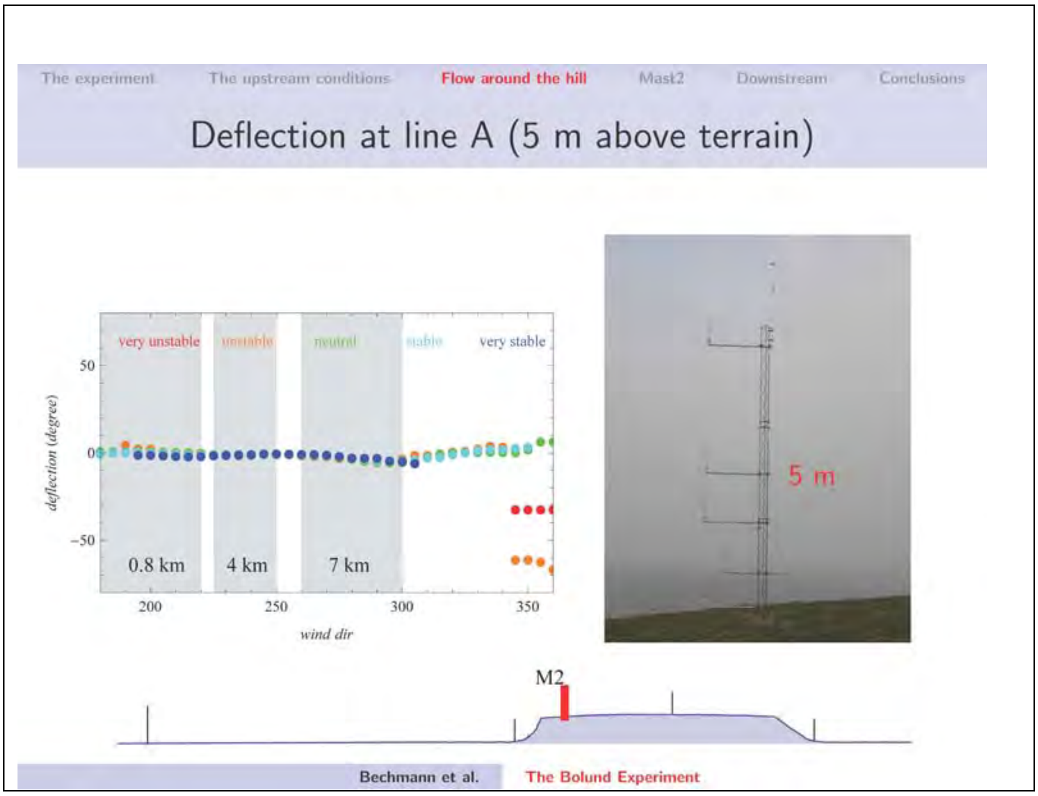
The experiment The upstream conditions **Flow around the hill** Mast2 Downstream Conclusions

Tilt at line A (5 m above terrain)



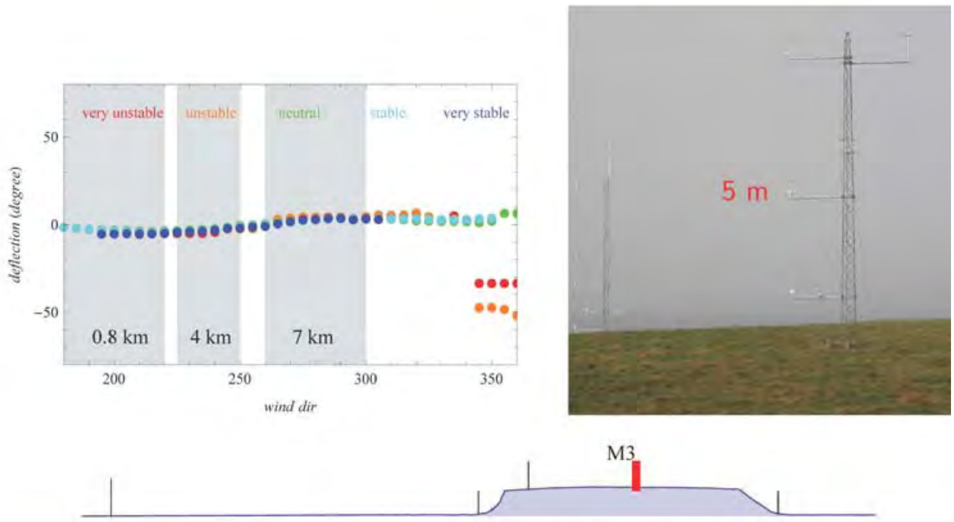
Bechmann et al. The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Deflection at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
deflection (degree)
50
0
−50
0.8 km
4 km
7 km
200
250
300
350
wind dir
5 m
M1
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Deflection at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
deflection (degree)
50
0
−50
0.8 km
4 km
7 km
200
250
300
350
wind dir
5 m
M2
Bechmann et al.
The Bolund Experiment

The experiment The upstream conditions **Flow around the hill** Mast2 Downstream Conclusions

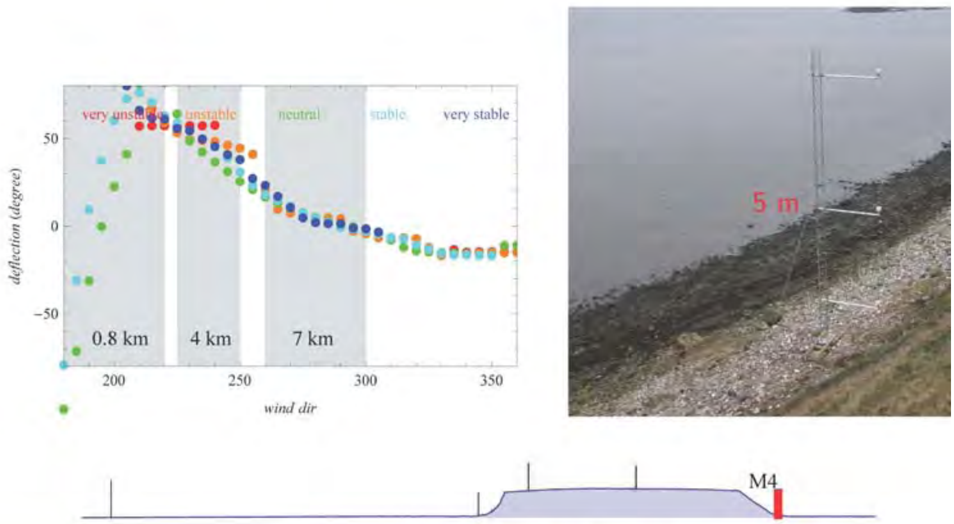
Deflection at line A (5 m above terrain)



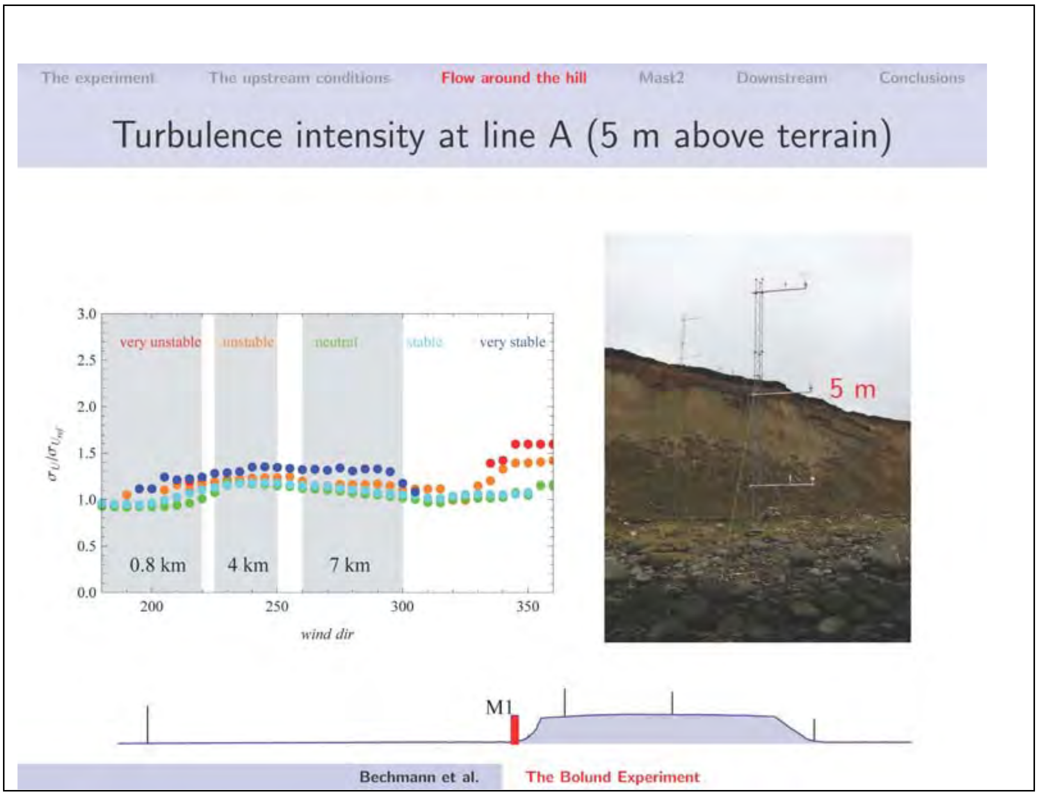
Bechmann et al. **The Bolund Experiment**

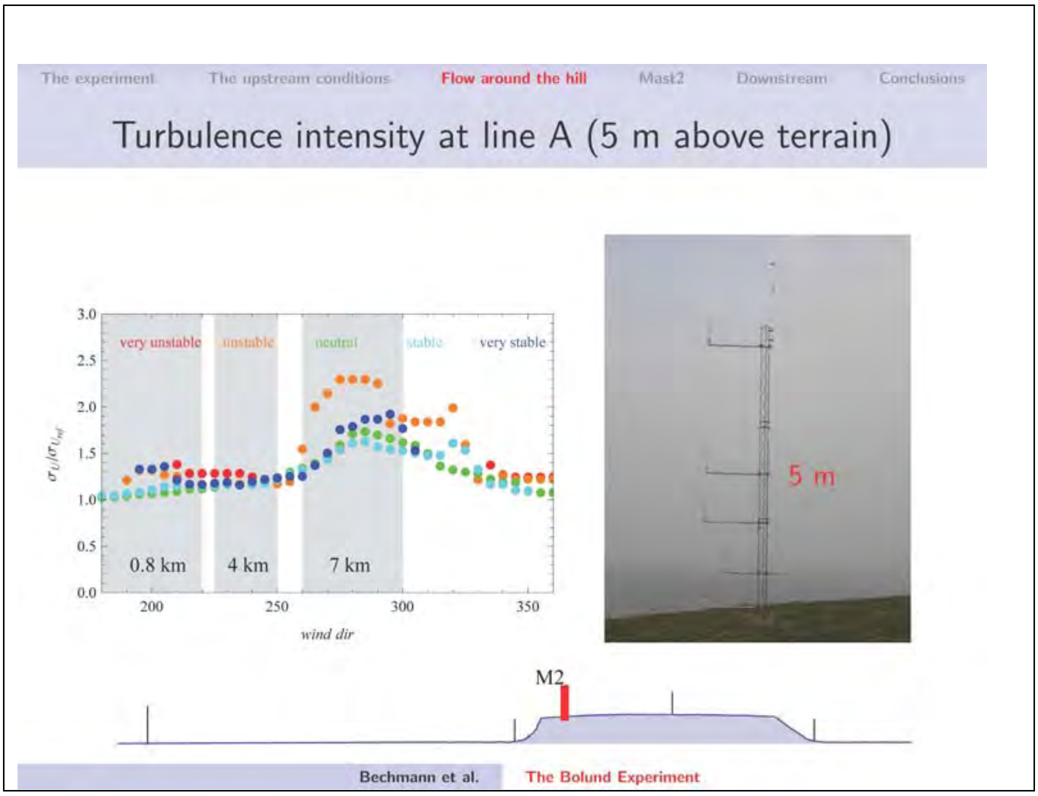
The experiment The upstream conditions **Flow around the hill** Mast2 Downstream Conclusions

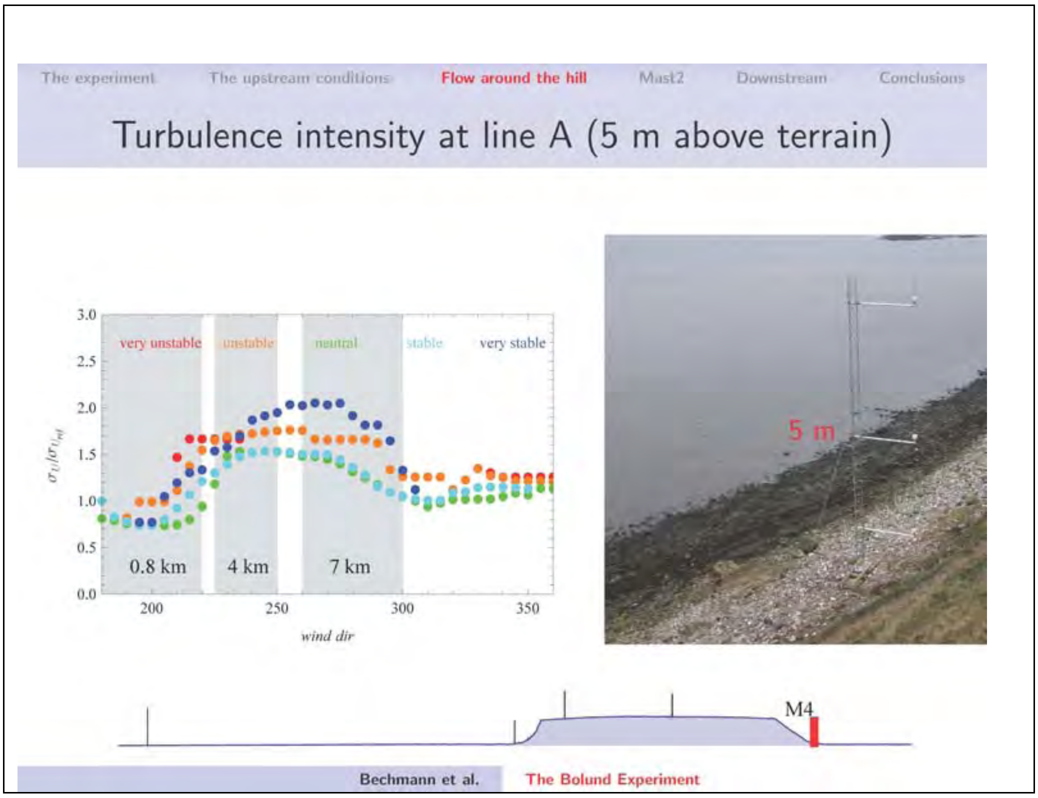
Deflection at line A (5 m above terrain)

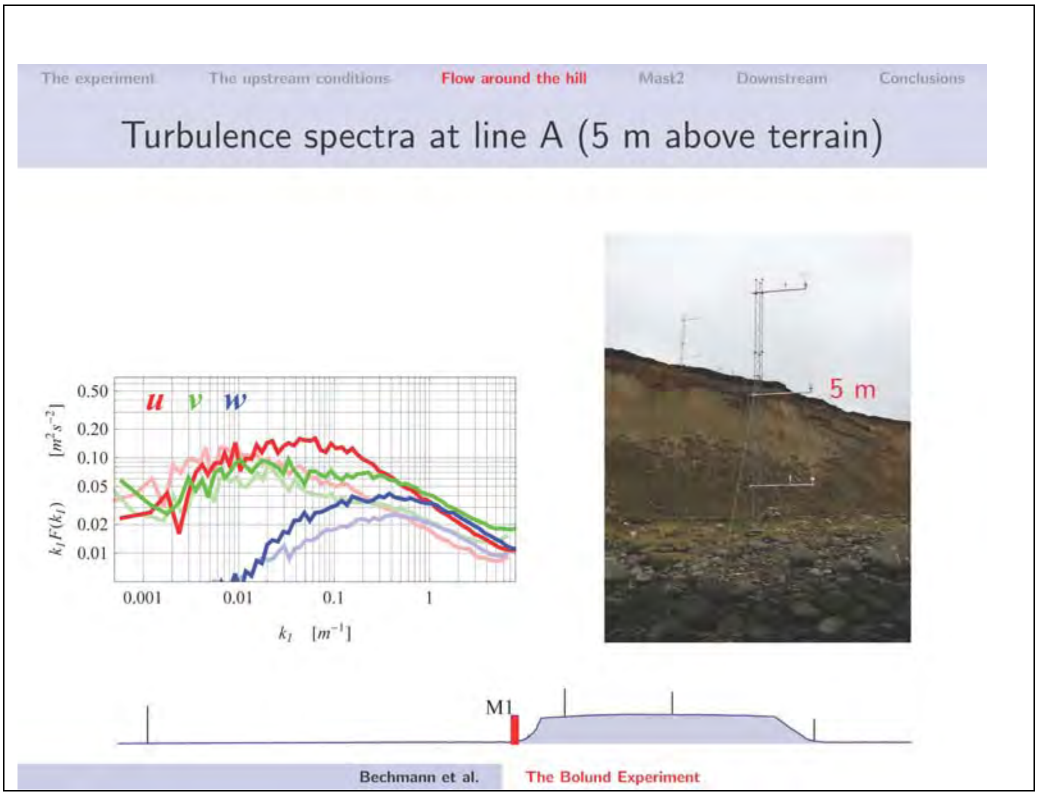


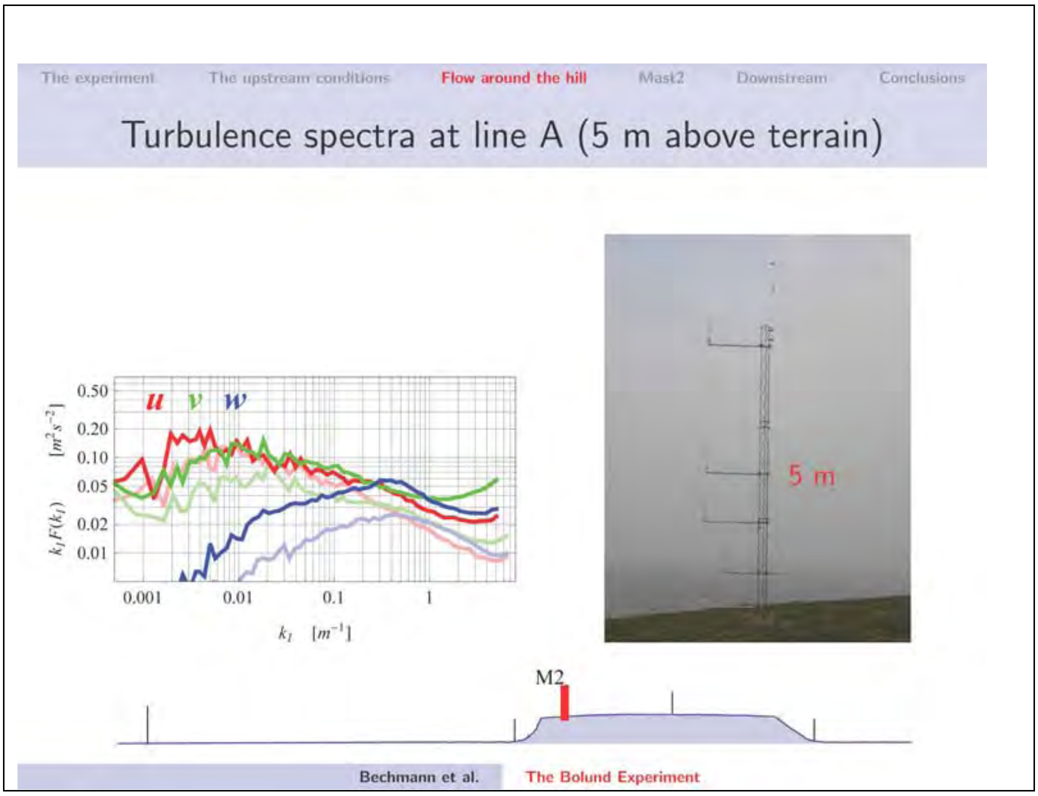
Bechmann et al. **The Bolund Experiment**

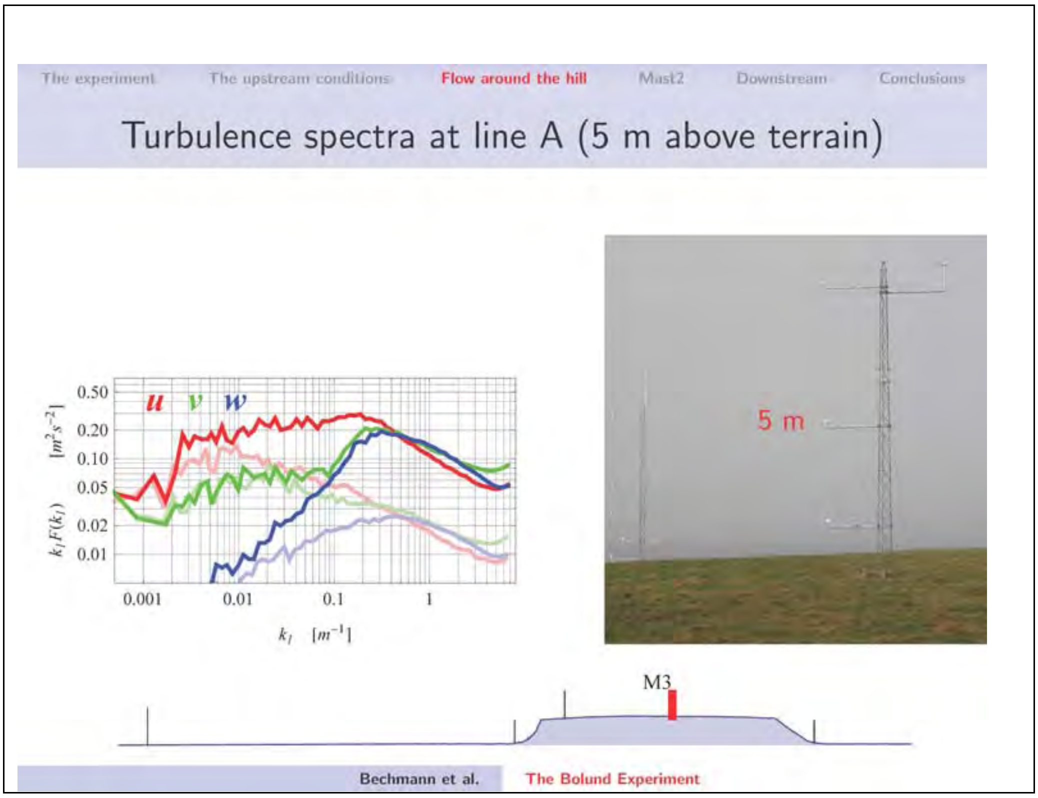

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence intensity at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
wind dir
5 m
M1
Bechmann et al.
The Bolund Experiment

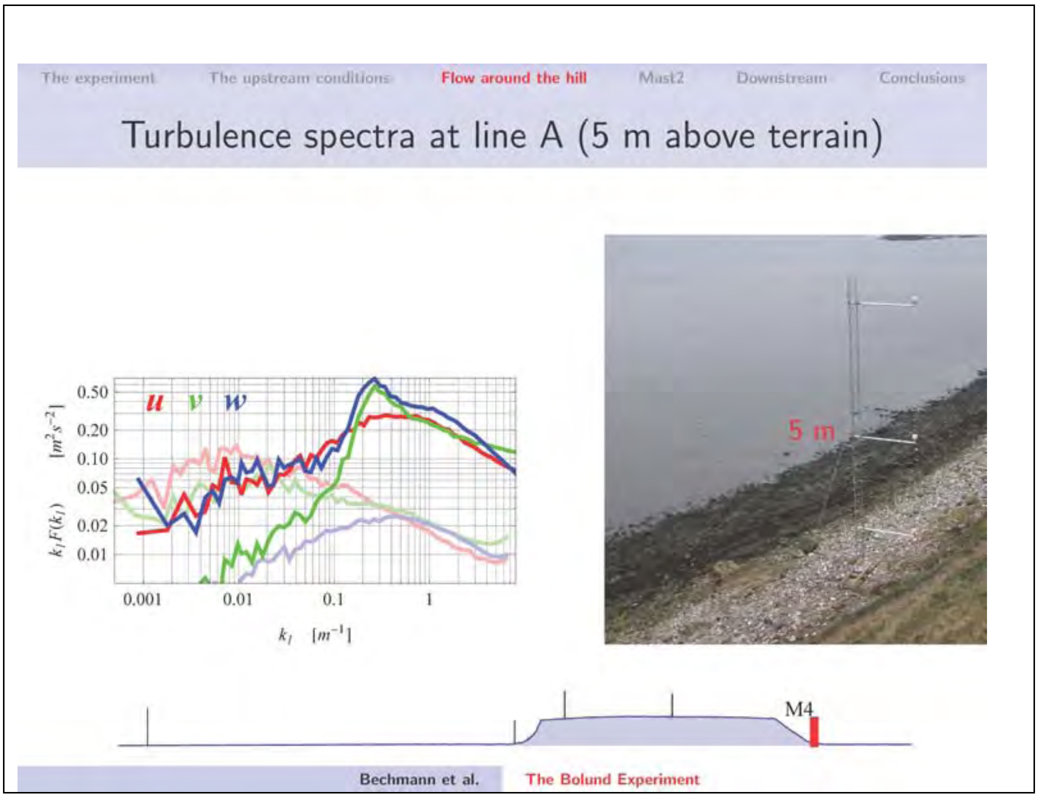

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence intensity at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
wind dir
5 m
M2
Bechmann et al.
The Bolund Experiment

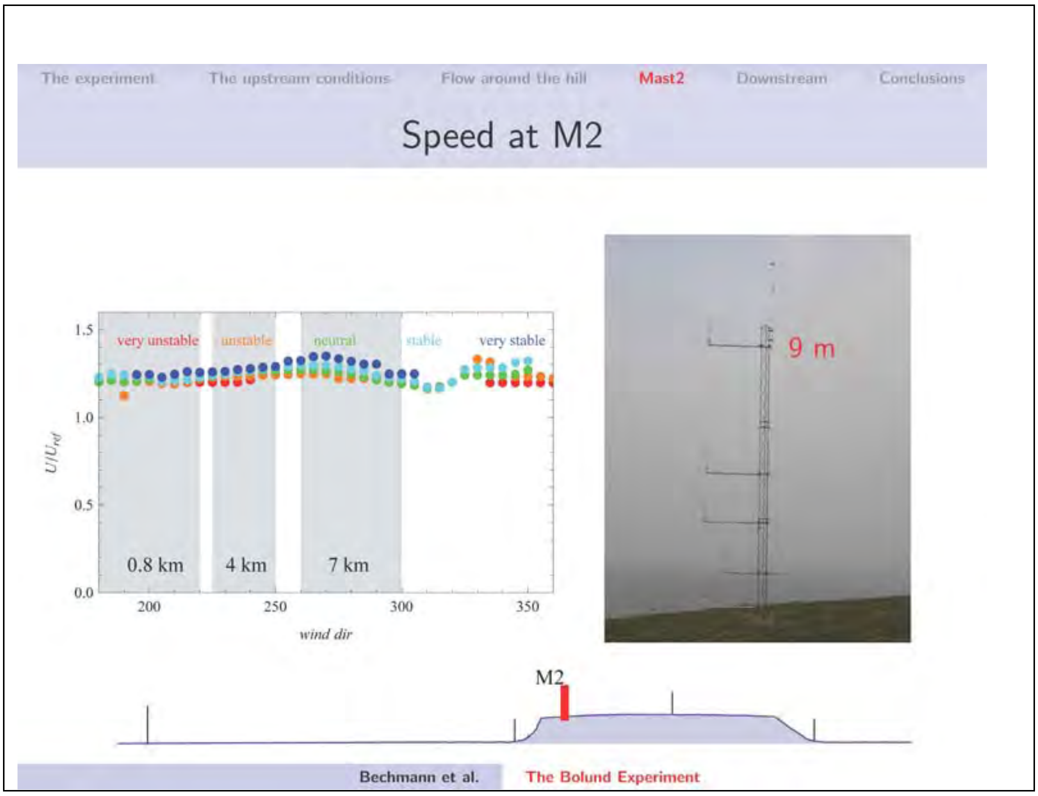

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence intensity at line A (5 m above terrain)
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
wind dir
5 m
M4
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence spectra at line A (5 m above terrain)
u
v
w
5 m
M1
Bechmann et al.
The Bolund Experiment

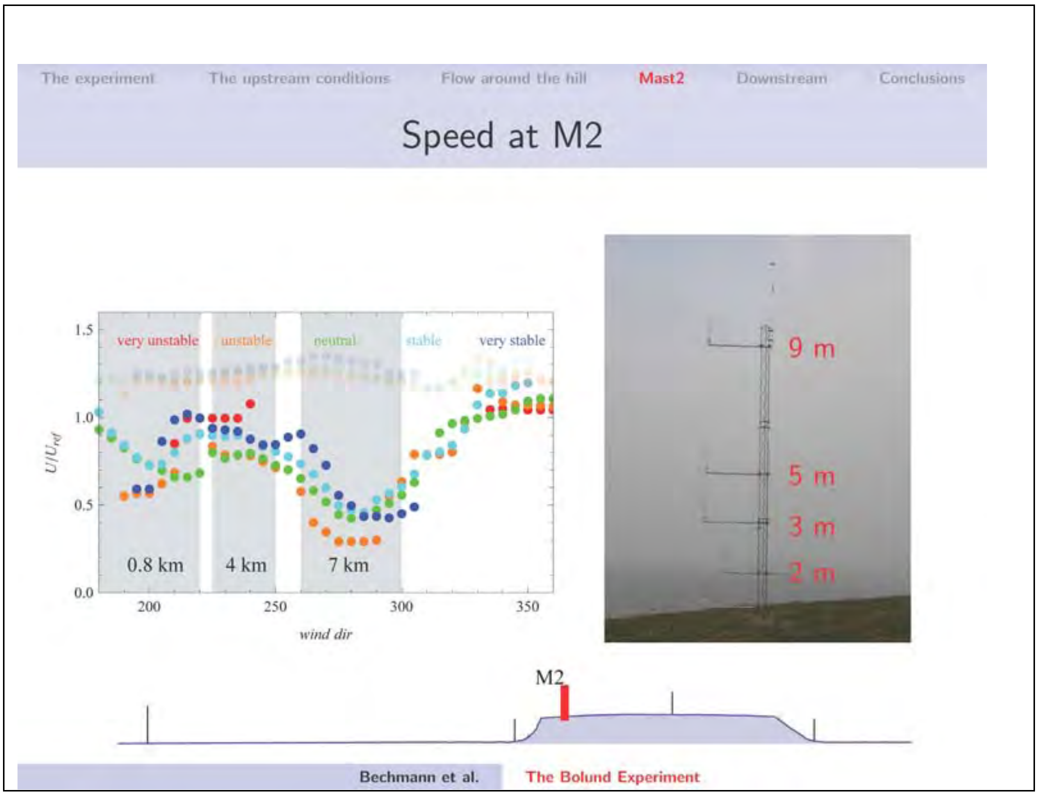

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence spectra at line A (5 m above terrain)
u v w
0.50
0.20
0.10
0.05
0.02
0.01
$k_1F(k_1)$ $[m^2s^{-2}]$
0.001
0.01
0.1
1
k_1 $[m^{-1}]$
5 m
M2
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence spectra at line A (5 m above terrain)
u v w
0.50
0.20
0.10
0.05
0.02
0.01
$k_1F(k_1)$ $[m^2s^{-2}]$
0.001
0.01
0.1
1
k_1 $[m^{-1}]$
5 m
M3
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence spectra at line A (5 m above terrain)
u v w
0.50
0.20
0.10
0.05
0.02
0.01
$k_1F(k_1)$ $[m^2s^{-2}]$
0.001
0.01
0.1
1
k_1 $[m^{-1}]$
5 m
M4
Bechmann et al.
The Bolund Experiment

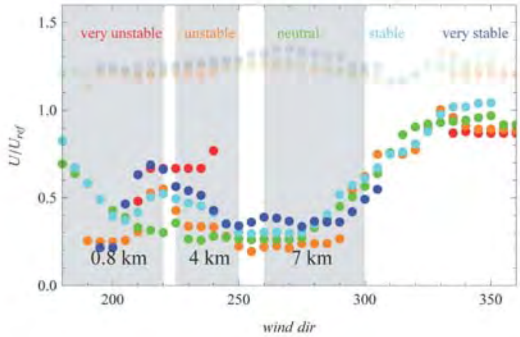

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Speed at M2
very unstable
unstable
neutral
stable
very stable
1.5
1.0
0.5
0.0
U/U_{ref}
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
M2
Bechmann et al.
The Bolund Experiment

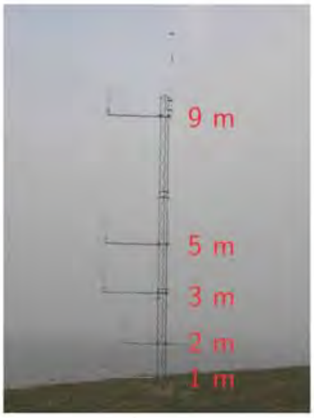

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Speed at M2
very unstable
unstable
neutral
stable
very stable
U/U_{ref}
1.5
1.0
0.5
0.0
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
5 m
3 m
M2
Bechmann et al.
The Bolund Experiment

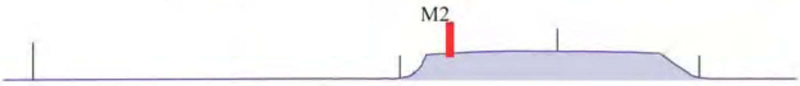

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Speed at M2
very unstable
unstable
neutral
stable
very stable
U/U_{ref}
1.5
1.0
0.5
0.0
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
5 m
3 m
2 m
M2
Bechmann et al.
The Bolund Experiment

The experiment | The upstream conditions | Flow around the hill | **Mast2** | Downstream | Conclusions

Speed at M2



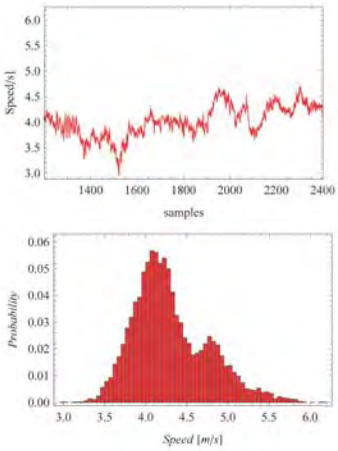


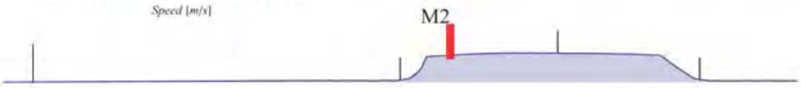


Bechmann et al. | The Bolund Experiment

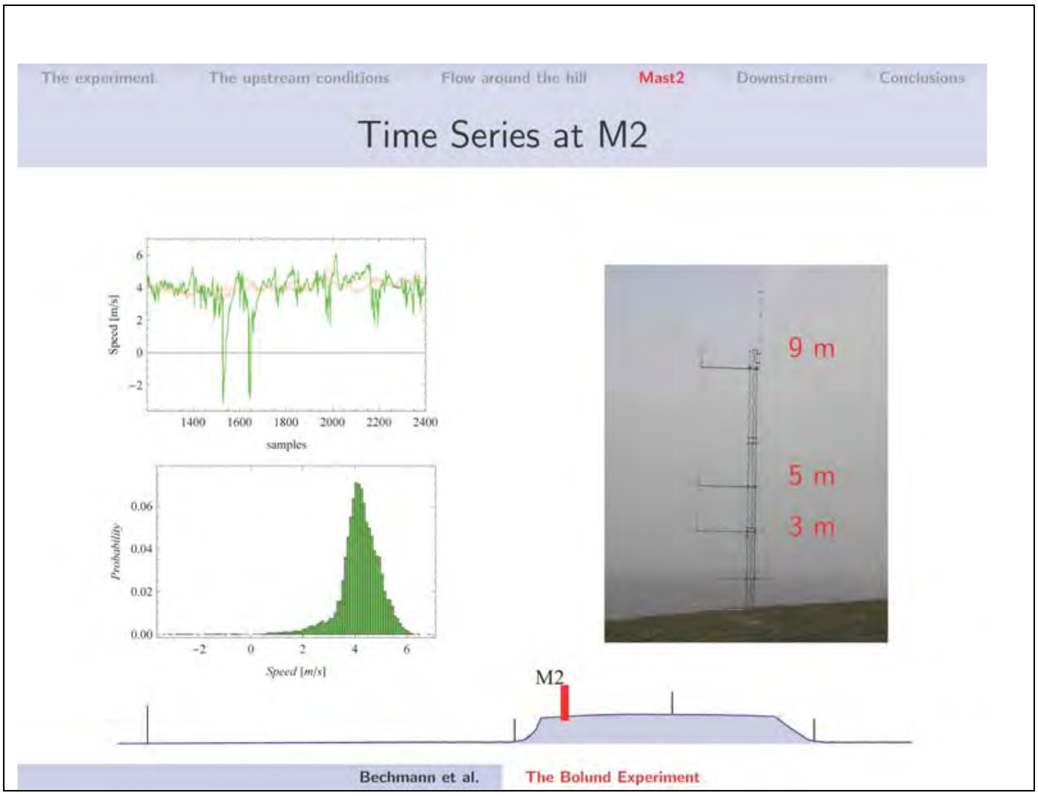
The experiment | The upstream conditions | Flow around the hill | **Mast2** | Downstream | Conclusions

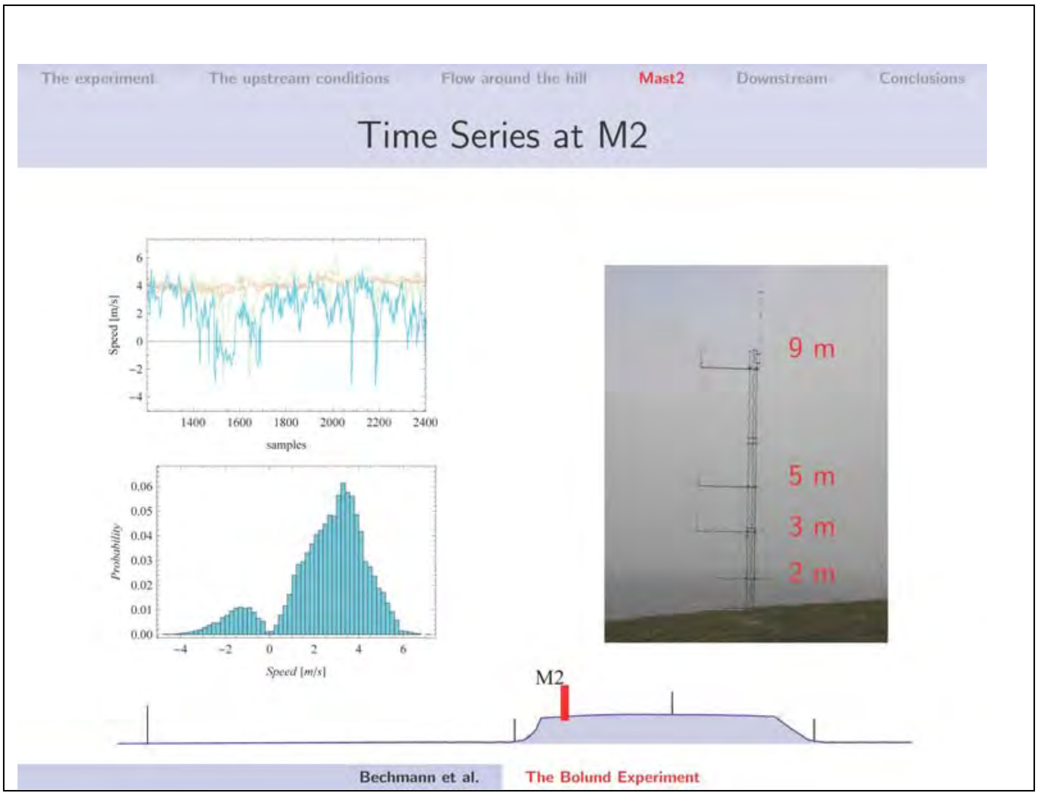
Time Series at M2

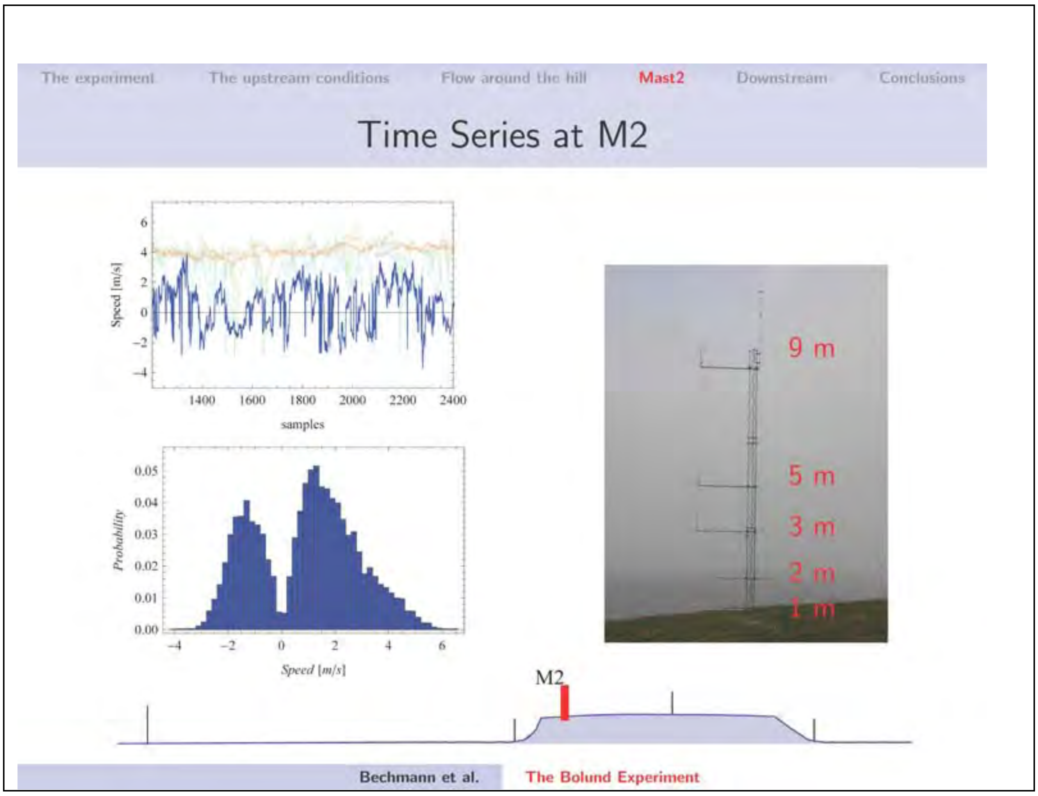




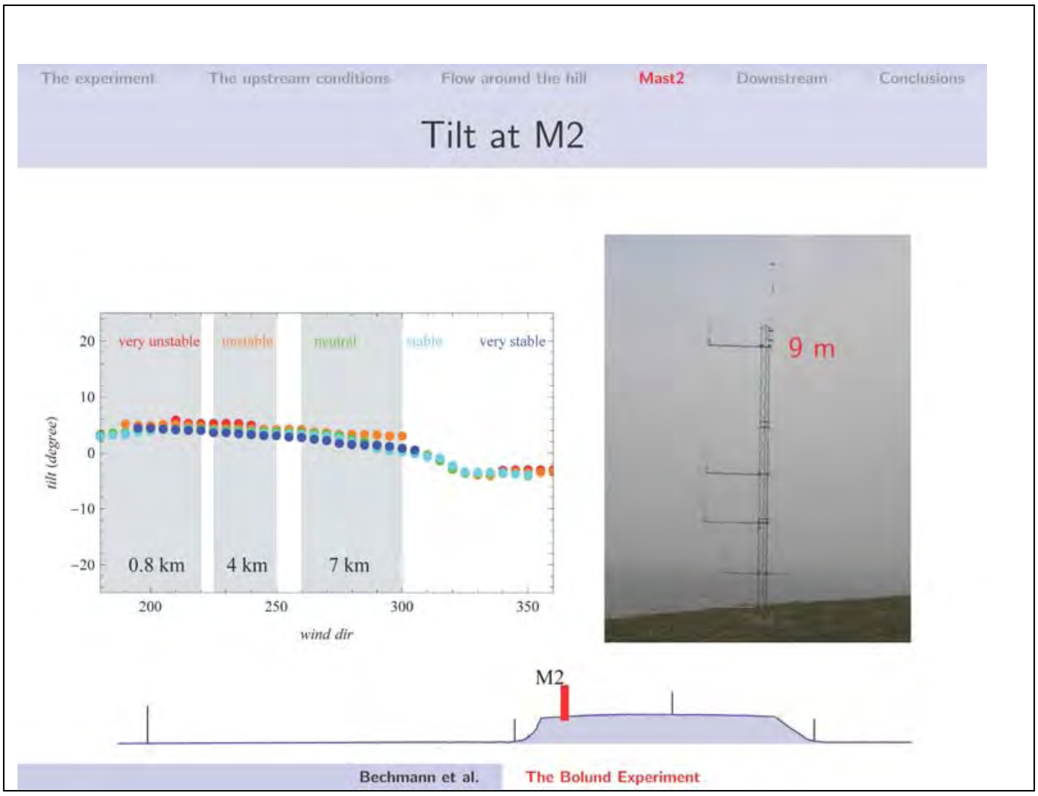
Bechmann et al. | The Bolund Experiment


The experiment The upstream conditions Flow around the hill Mast2 Downstream Conclusions
Time Series at M2
Speed [m/s]
samples
Probability
Speed [m/s]
9 m
5 m
3 m
M2
Bechmann et al.
The Bolund Experiment

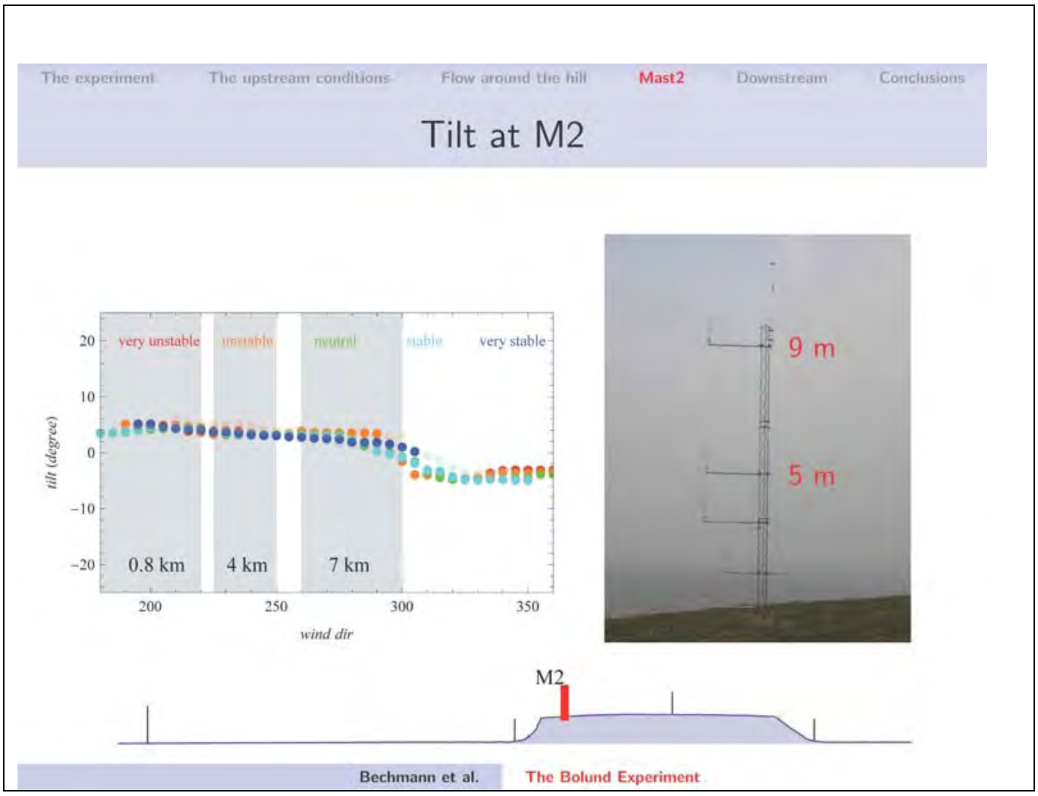

The experiment The upstream conditions Flow around the hill Mast2 Downstream Conclusions
Time Series at M2
Speed [m/s]
samples
Probability
Speed [m/s]
9 m
5 m
3 m
2 m
M2
Bechmann et al.
The Bolund Experiment



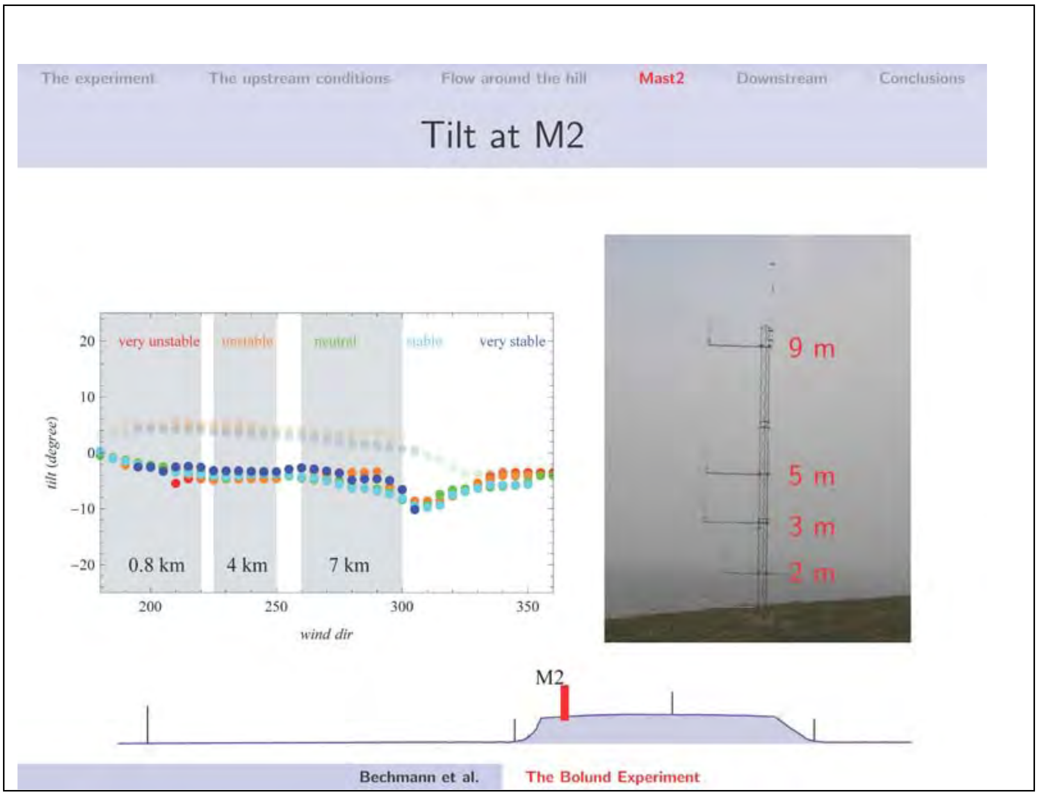
The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Time Series at M2
Speed [m/s]
samples
Probability
Speed [m/s]
9 m
5 m
3 m
2 m
1 m
M2
Bechmann et al.
The Bolund Experiment



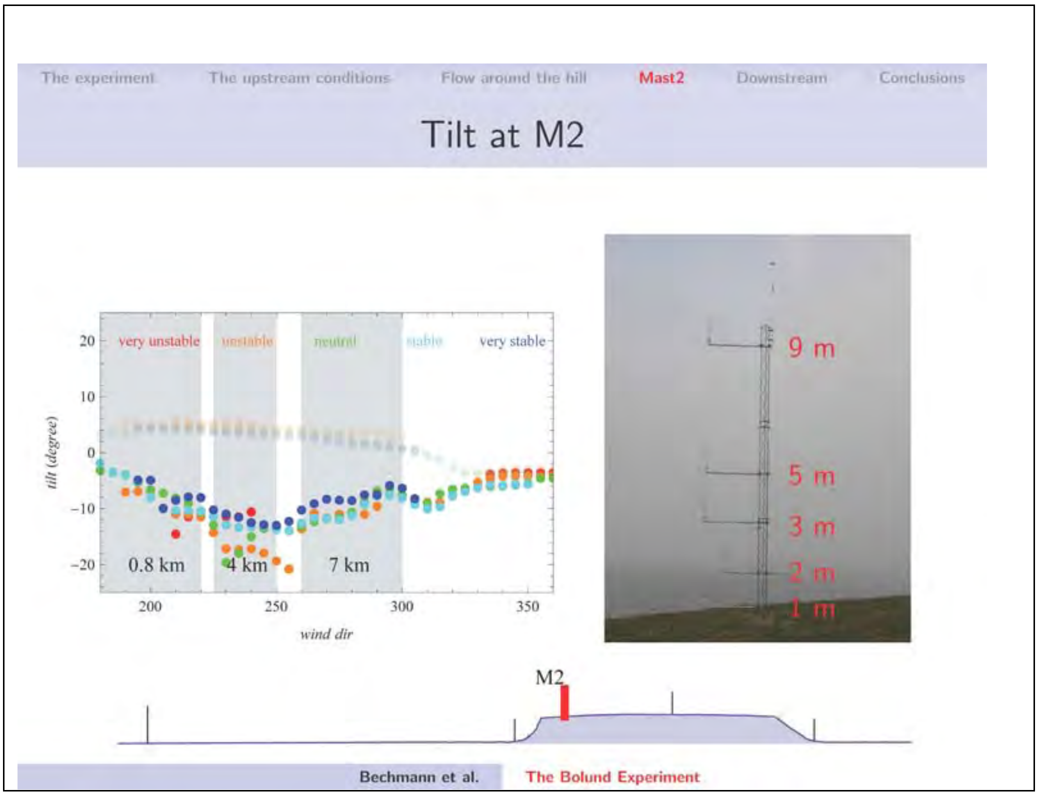
The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Tilt at M2
very unstable
unstable
neutral
stable
very stable
tilt (degree)
0.8 km
4 km
7 km
wind dir
9 m
M2
Bechmann et al.
The Bolund Experiment

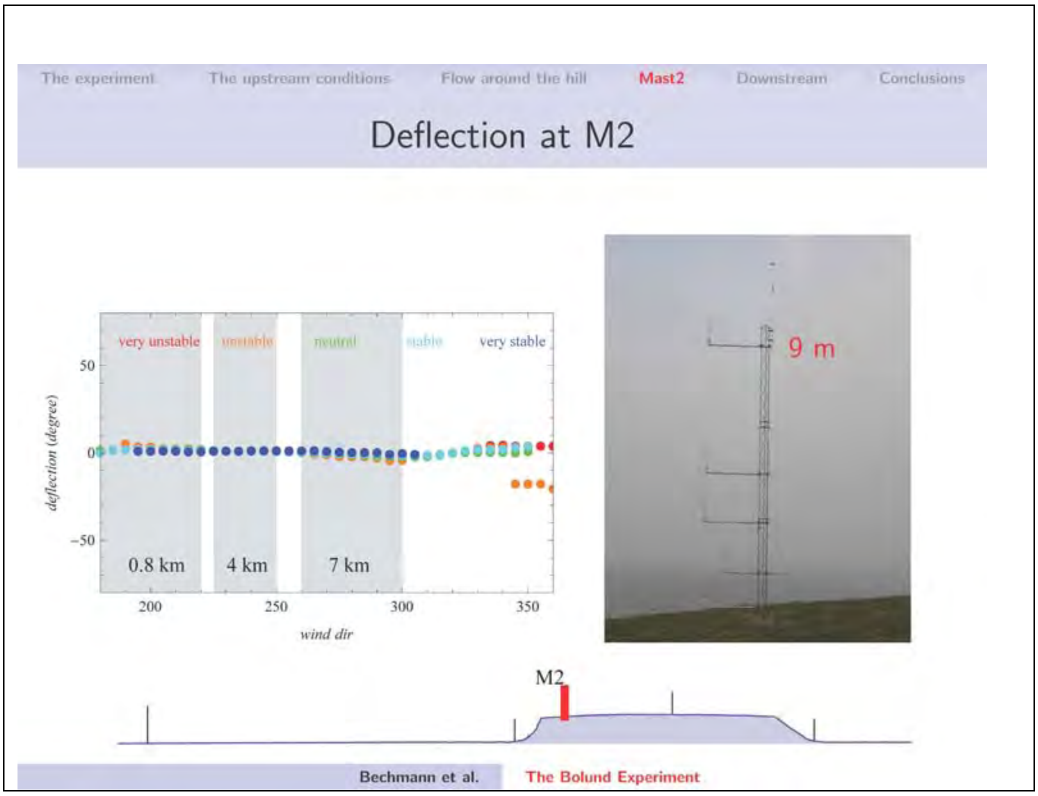


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Tilt at M2
very unstable
unstable
neutral
stable
very stable
tilt (degree)
0.8 km
4 km
7 km
wind dir
9 m
5 m
M2
Bechmann et al.
The Bolund Experiment

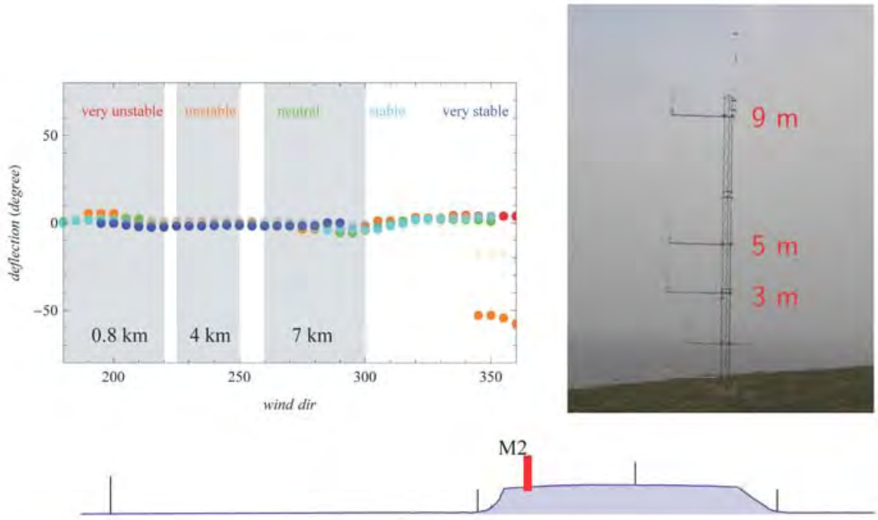


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Tilt at M2
very unstable
unstable
neutral
stable
very stable
tilt (degree)
0.8 km
4 km
7 km
wind dir
9 m
5 m
3 m
2 m
M2
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Tilt at M2
very unstable
unstable
neutral
stable
very stable
tilt (degree)
20
10
0
−10
−20
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
5 m
3 m
2 m
1 m
M2
Bechmann et al.
The Bolund Experiment

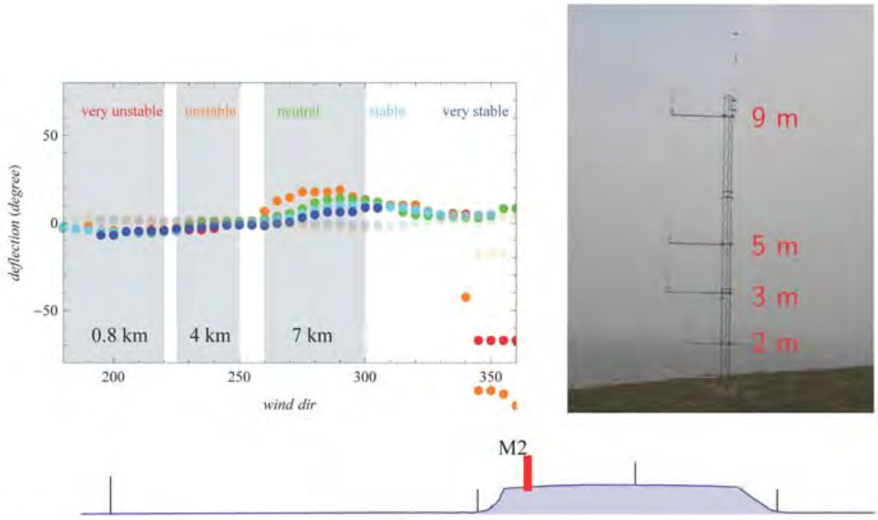

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Deflection at M2
very unstable
unstable
neutral
stable
very stable
deflection (degree)
50
0
−50
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
M2
Bechmann et al.
The Bolund Experiment

Deflection at M2

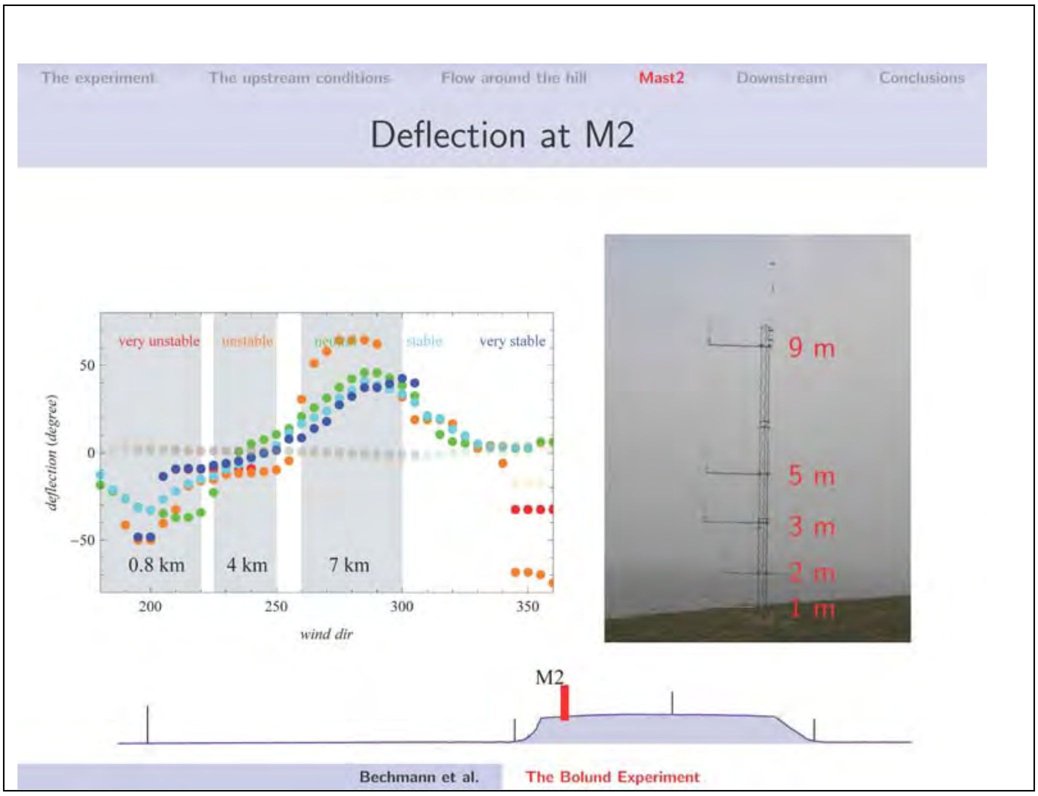


The experiment The upstream conditions Flow around the hill Mast2 Downstream Conclusions

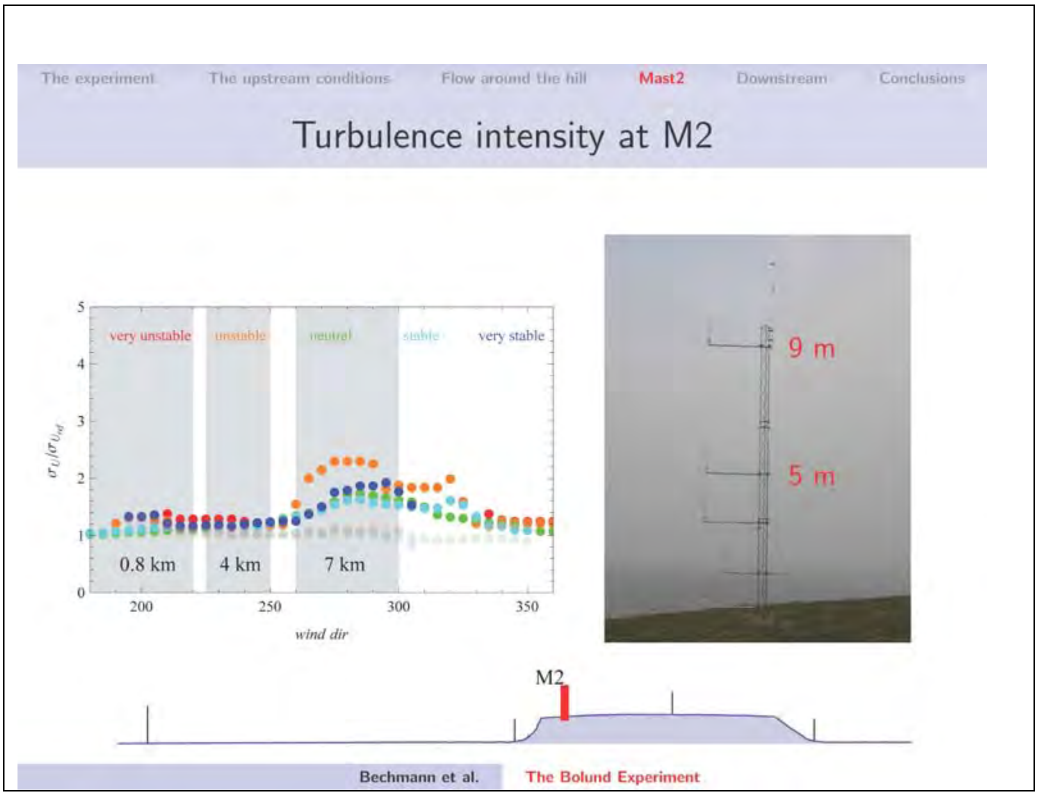
Deflection at M2



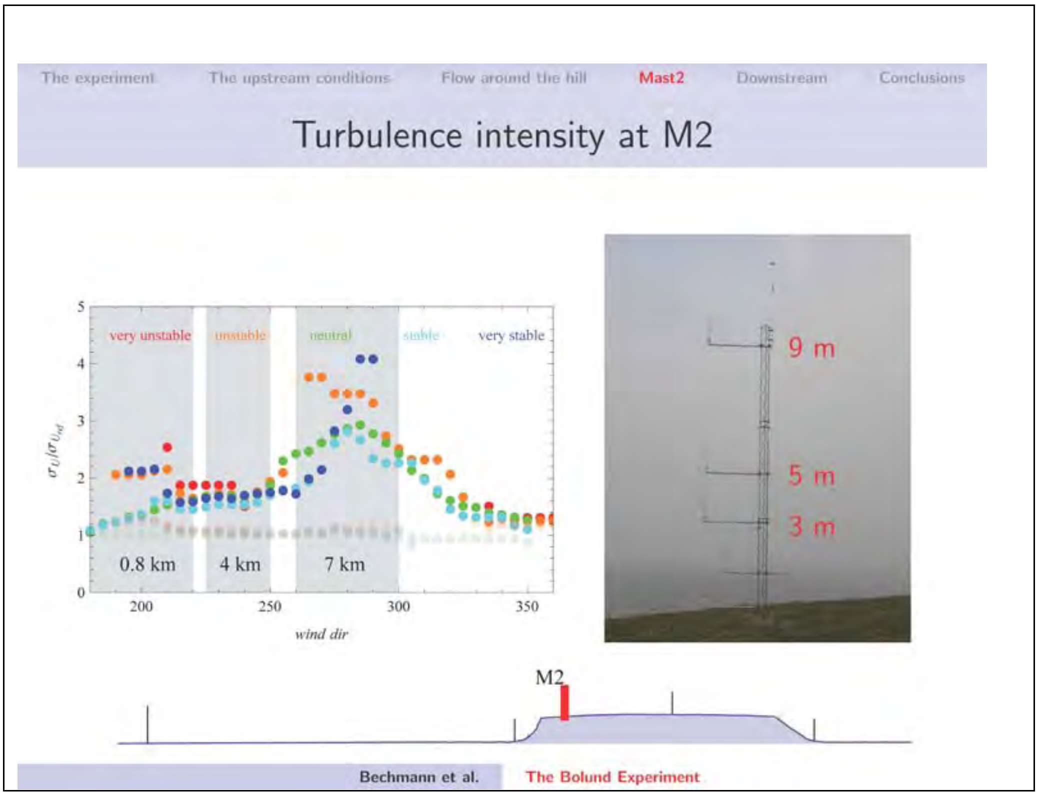
Bechmann et al. The Bolund Experiment

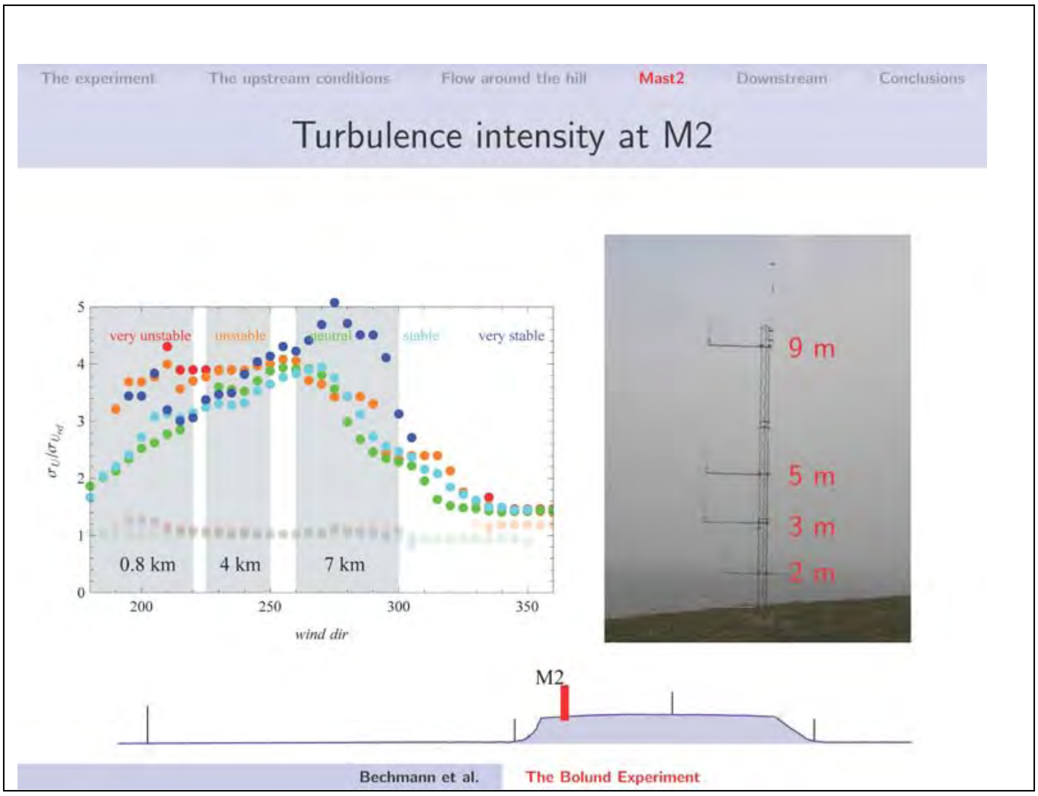


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Deflection at M2
very unstable
unstable
neutral
stable
very stable
deflection (degree)
50
0
−50
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
5 m
3 m
2 m
1 m
M2
Bechmann et al.
The Bolund Experiment

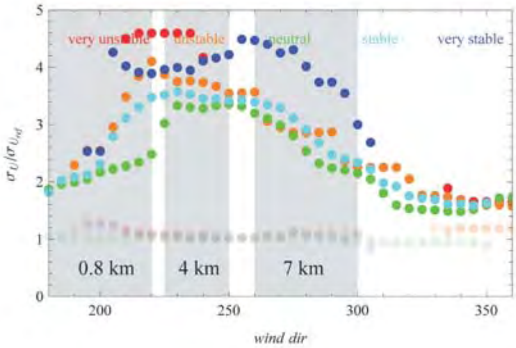


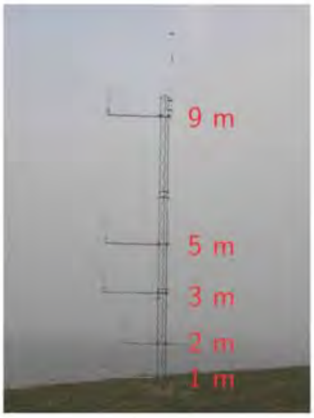
The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence intensity at M2
very unstable
unstable
neutral
stable
very stable
5
4
3
2
1
0
0.8 km
4 km
7 km
200
250
300
350
wind dir
9 m
5 m
M2
Bechmann et al.
The Bolund Experiment

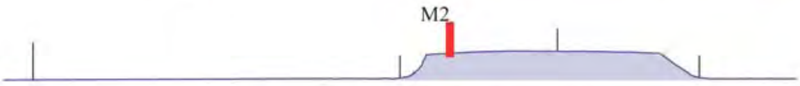

The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence intensity at M2
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
wind dir
9 m
5 m
3 m
M2
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
Turbulence intensity at M2
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
wind dir
9 m
5 m
3 m
2 m
M2
Bechmann et al.
The Bolund Experiment

Turbulence intensity at M2



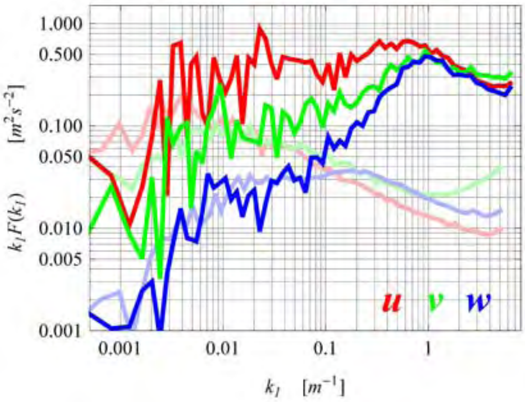


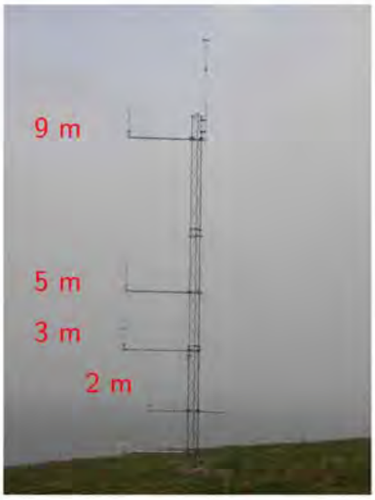


Turbulence spectra at Mast 2 (239 degrees)

The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Turbulence spectra at Mast 2 (239 degrees)

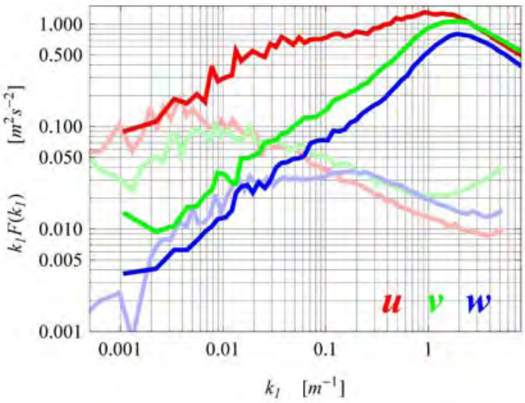




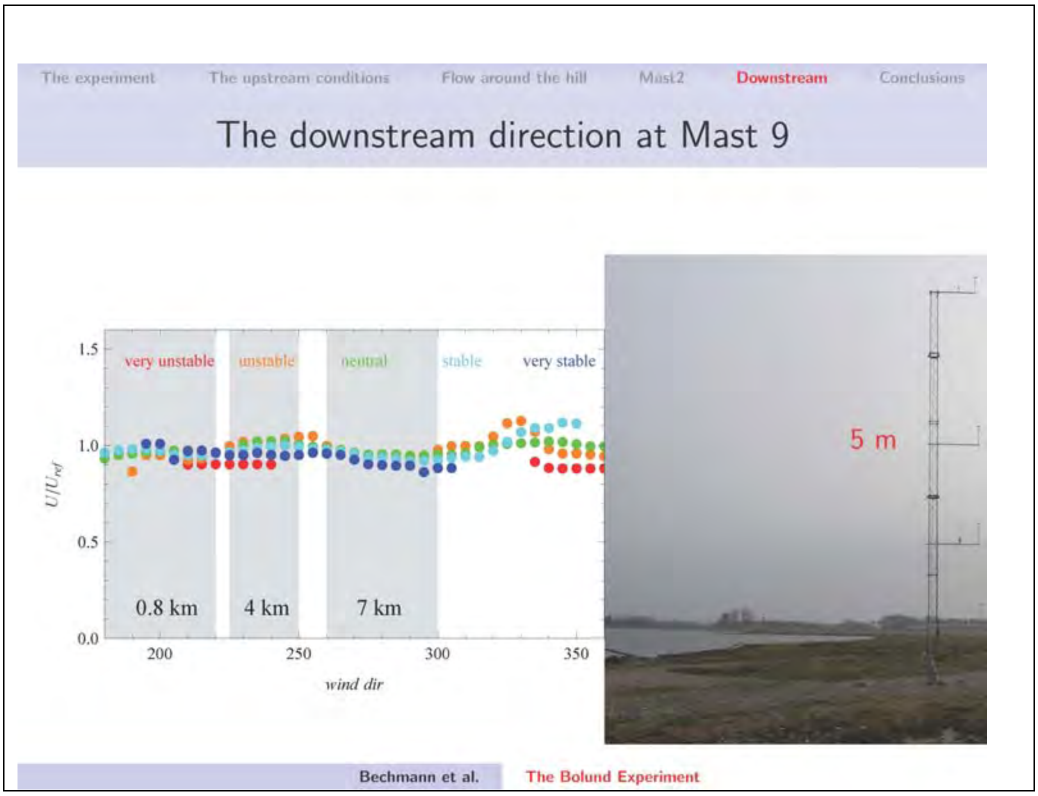
Bechmann et al. The Bolund Experiment

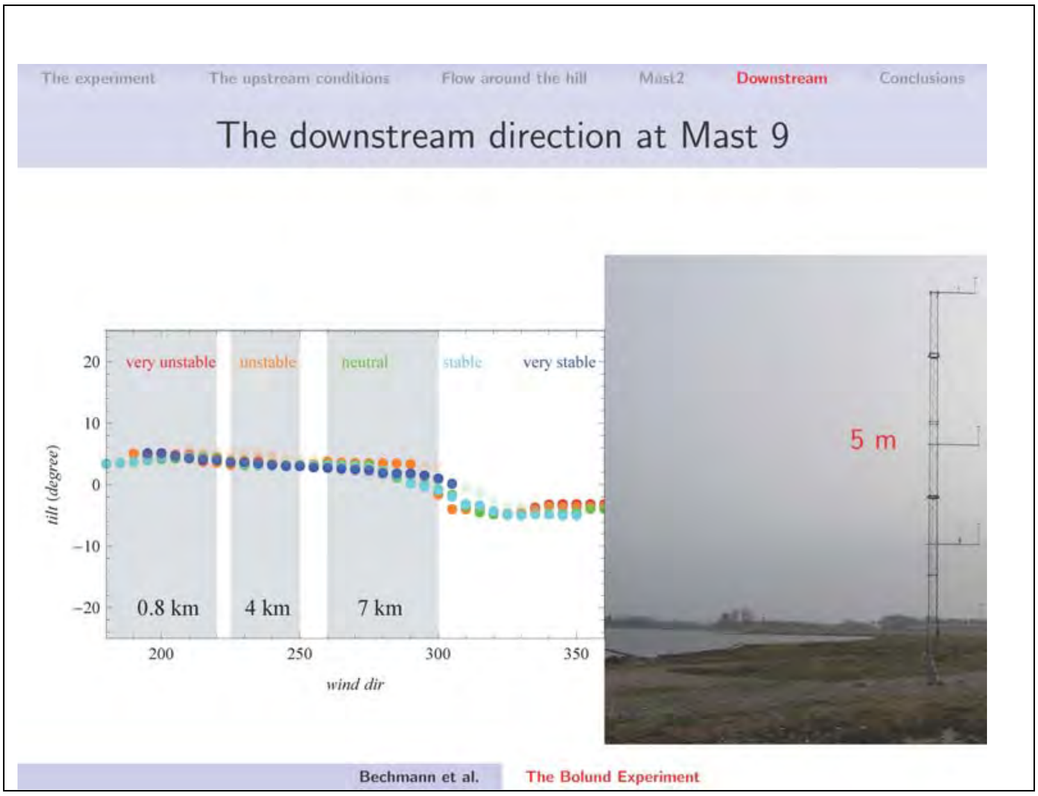
The experiment | The upstream conditions | Flow around the hill | Mast2 | Downstream | Conclusions

Turbulence spectra at Mast 2 (239 degrees)

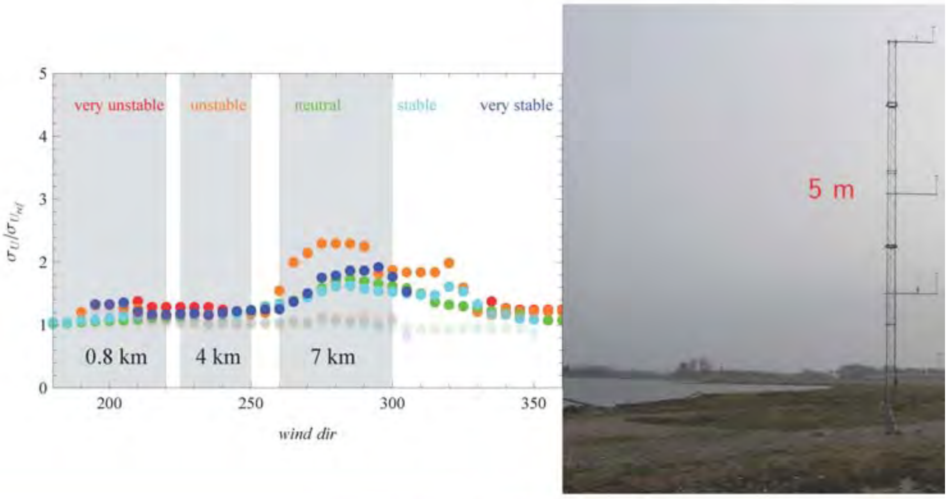


Bechmann et al. The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
The downstream direction at Mast 9
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
U/U_{ref}
wind dir
5 m
Bechmann et al.
The Bolund Experiment


The experiment
The upstream conditions
Flow around the hill
Mast2
Downstream
Conclusions
The downstream direction at Mast 9
very unstable
unstable
neutral
stable
very stable
0.8 km
4 km
7 km
tilt (degree)
wind dir
5 m
Bechmann et al.
The Bolund Experiment

The downstream direction at Mast 9



Conclusions

- Instrumentation and data acquisition worked well. Proximity to Risø very convenient.
- We have successfully captured the gross features of flow over a steep hill.
- No significant stability effects
- Very turbulent recirculation zones behind hill and at "leading edge".
- At the downstream mast M9 the flow relaxed to normal.
- Should we do it over again: Only measurements along one line, but more heavily instrumented

“Blind Comparison Results” - by Andreas Bechmann

DTU

Results of the Blind Comparison

Risø DTU: **Andreas Bechmann** (andh@risoe.dtu.dk),
Pierre-Elouan Rethore, Mike Courtney, Hans E. Jørgensen,
Jacob Berg, Jakob Mann and Niels N. Sørensen
Vestas Technology R&D: Lars Chr. Christensen
and many others ...

Risø DTU
National Laboratory for Sustainable Energy

Vestas

DTU

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1. Introduction
2. Measurements & Simulations
3. Results
4. Analysis
5. Conclusions

2 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Introduction: Purpose of Blind Comparison

1. **Make The Bolund Data Visible**
2. **Evaluate Flow Modeling Accuracy**
   (TPWind: uncertainty less than 3% [1])
3. **Standardize Resource Assessment Modeling?**
   (Top Priority of TPWind)

[1]European Wind Energy Technology Platform. Strategic research agenda, market deployment strategy, from 2008 to 2030

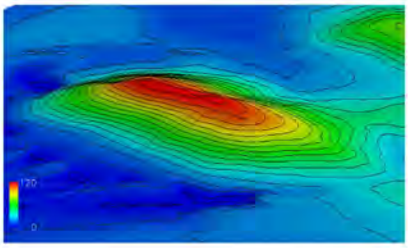
Introduction: 1. The Bolund Data

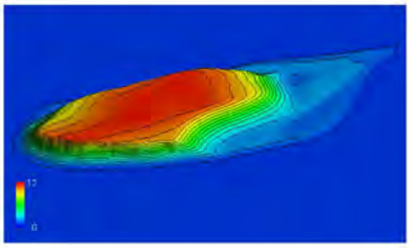
Askervein Experiment, 83

- Well-defined inflow conditions
- Well-defined and Uniform roughness
- 120m high
- Low hill / "simple" terrain

Bolund Experiment, 08

- Well-defined inflow conditions
- Well-defined roughness change
- 12m high
- Steep escarpment / "complex"





Introduction: 2. Evaluate Model Accuracy

Uncertainties:

- **Modeling** (Turb. model, Discretization, Experience)
- **Boundary Conditions** (Orography, Free wind description etc.)
- **Measurements**

Blind Comparison:

- **Evaluation of Modeling Accuracy** (Measure & BC Errors Minimized)
- **Evaluation of Different Approaches** (WAsP, CFD, Wind tunnel etc.)
- **Only constraint: Boundary Conditions** (Evaluation of state-of-the-art)

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Introduction: 3. Standardize the Modeling

52 Different Submissions,
52 Different Approaches,
52 Different Results!

Model types:

- 3: Experimental method
  - 1: Wind tunnel
  - 1: Flow channel
- 3: No answer
- 9: Linearized flow model
  - 3: WAsP like
  - 5: WAsP Eng.
- 0: Mesoscale model
- 37: Non-linear CFD model
  - 5: LES / hybrid RANS-LES
  - 7: RANS 1 eqn. (k-l, Spalart-Allmaras)
  - 25: RANS 2 eqn. (k-epsilon, k-omega)

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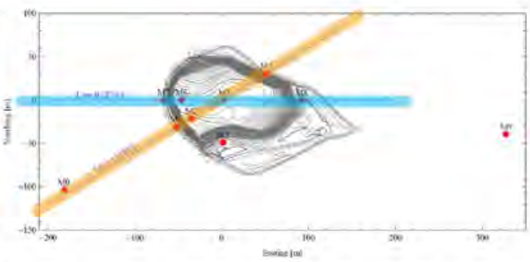
Measurements: Selected cases

data for 4 Cases:

1. 270 direction
2. 255 direction
3. 239 direction
4. 90 direction

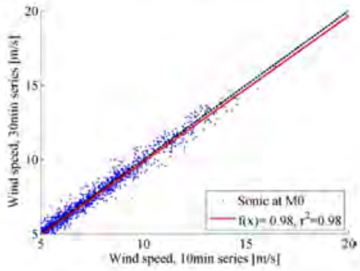
Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

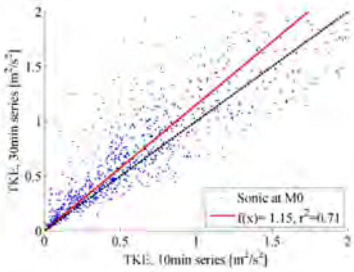


Measurements: Selecting Data

Selection Criteria (evaluated at upstream mast, M0/M9)

1. Wind direction: ± 8º
2. Monin-Obukhov length: $|1/L| < 0.004\ m^{-1}$ *(L > 250 m)*
3. Water level: ± 0.4 m
4. Wind speed 5 m agl: $5\ ms^{-1} < s < 12\ ms^{-1}$ *($z_0 \approx 1\text{-}5 \cdot 10^{-4}$ m, Charnock)*
5. 10 min time series

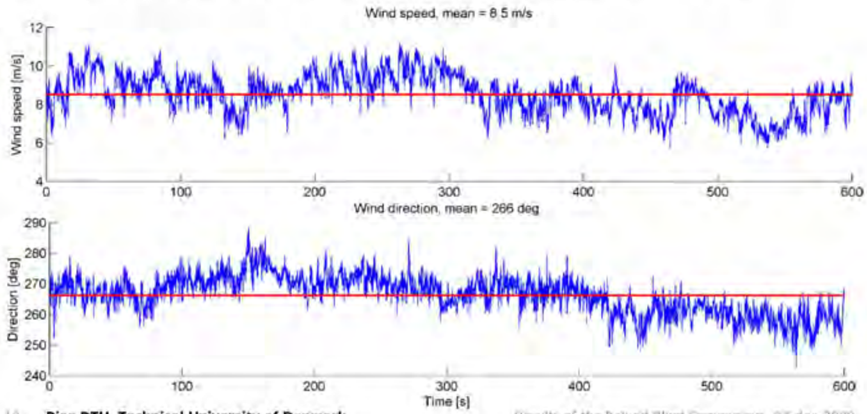




9 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Measurements: Comparing with Simulation

1. u*: 0.4 / 0.469 ms^{-1} (42 time-series) Direction: 270 / 268.4
2. u*: 0.4 / 0.582 ms^{-1} (25 time-series) Direction: 255 / 254.3
3. u*: 0.4 / 0.356 ms^{-1} (9 time-series) Direction: 239 / 241.7
4. u*: 0.5 / 0.509 ms^{-1} (19 time-series) Direction: 90 / 94.1



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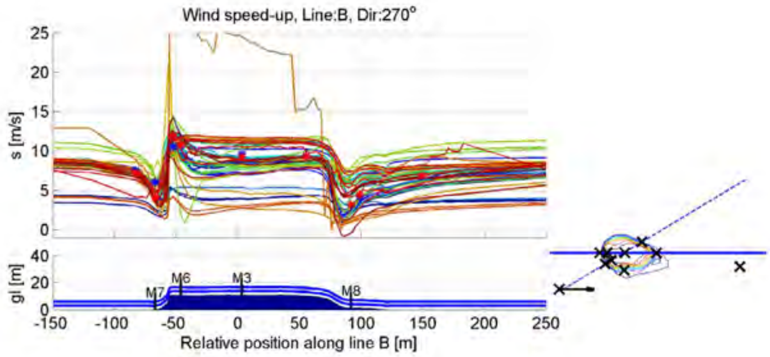
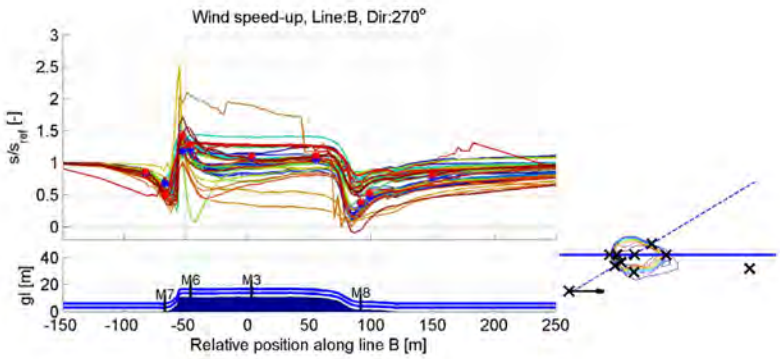
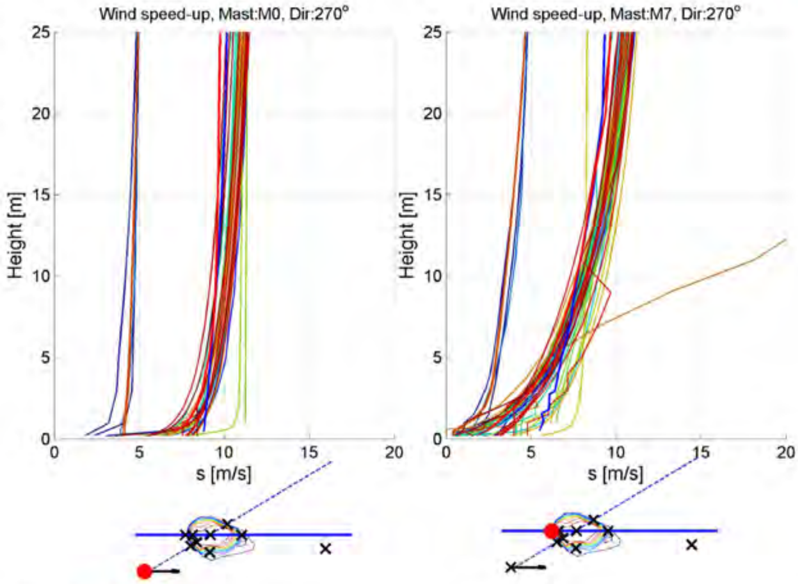
Simulation: Normalizing



Simulation: Normalizing

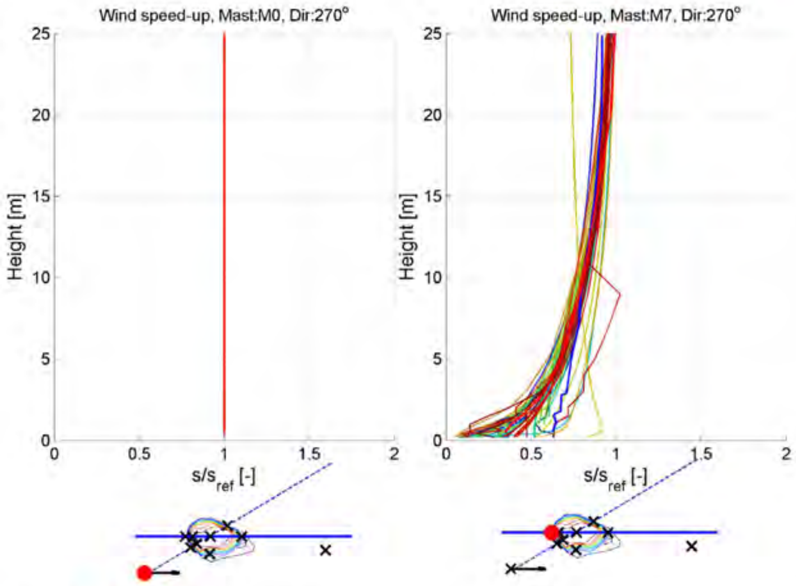


Simulation: Normalizing



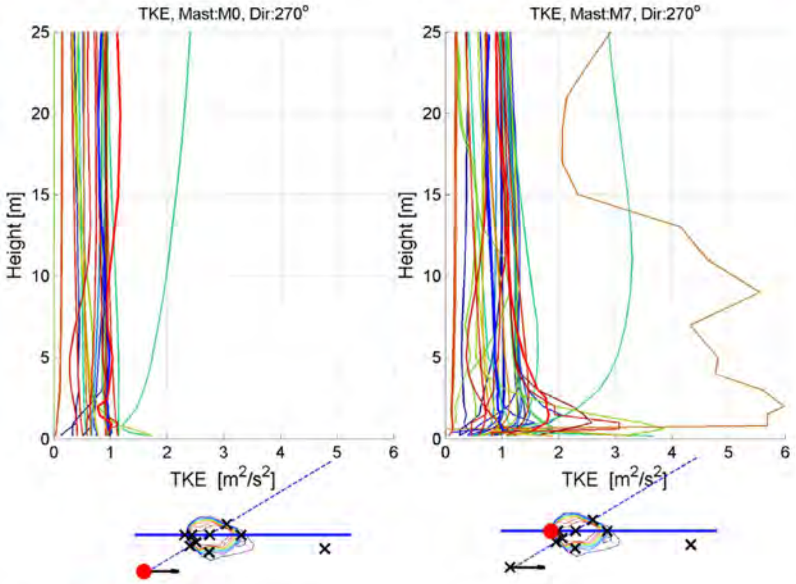
13 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Simulation: Normalizing



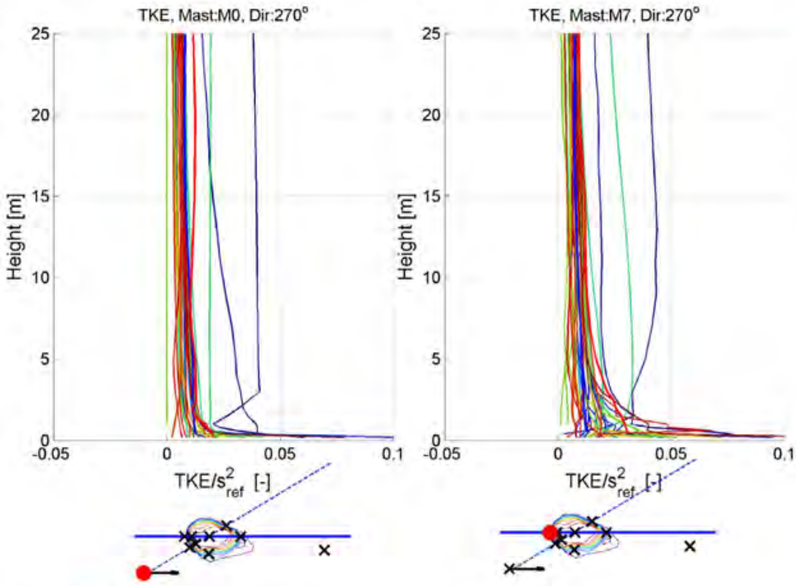
14 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Simulation: Normalizing



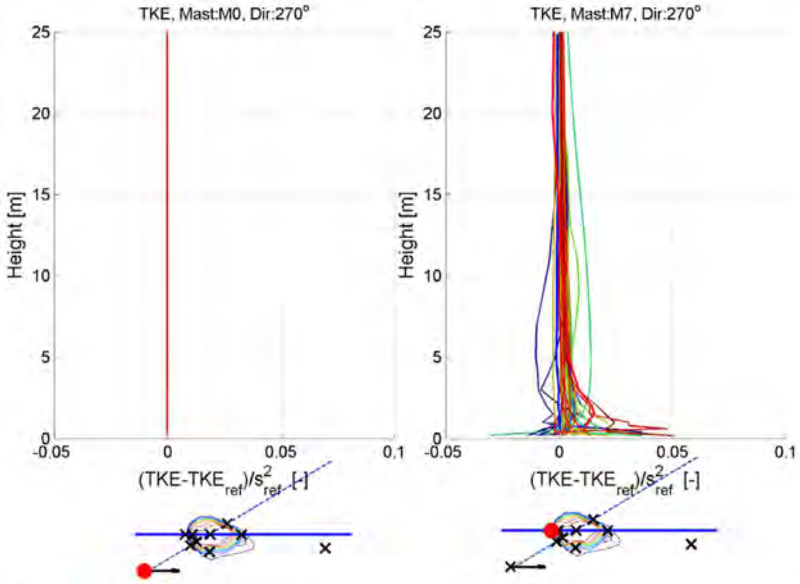
15 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Simulation: Normalizing



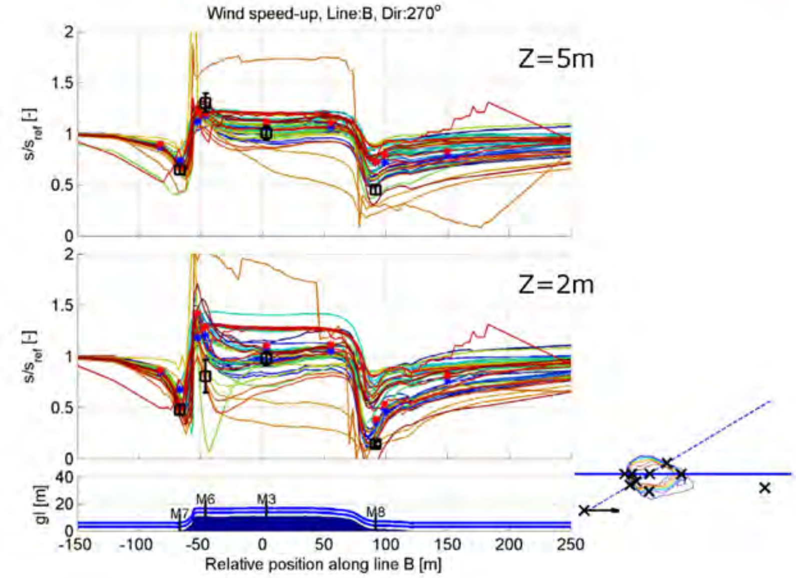
16 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Simulation: Normalizing

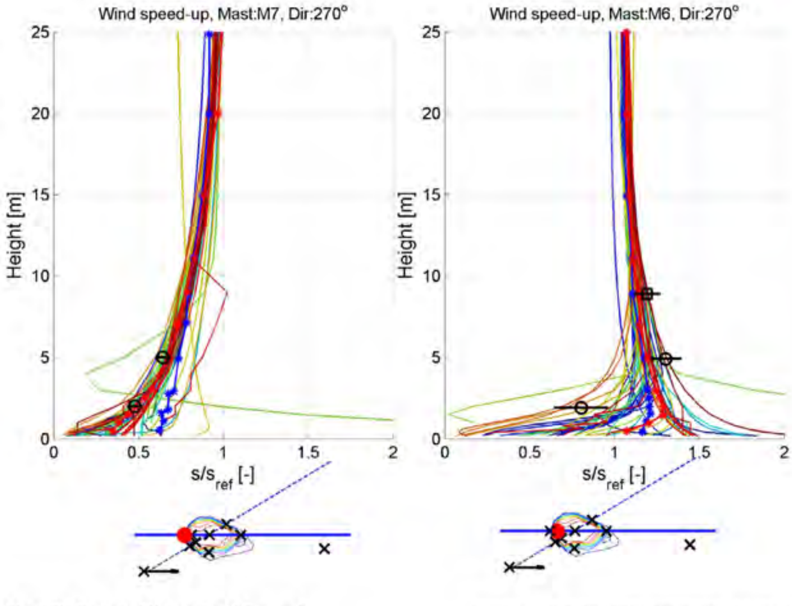


Content

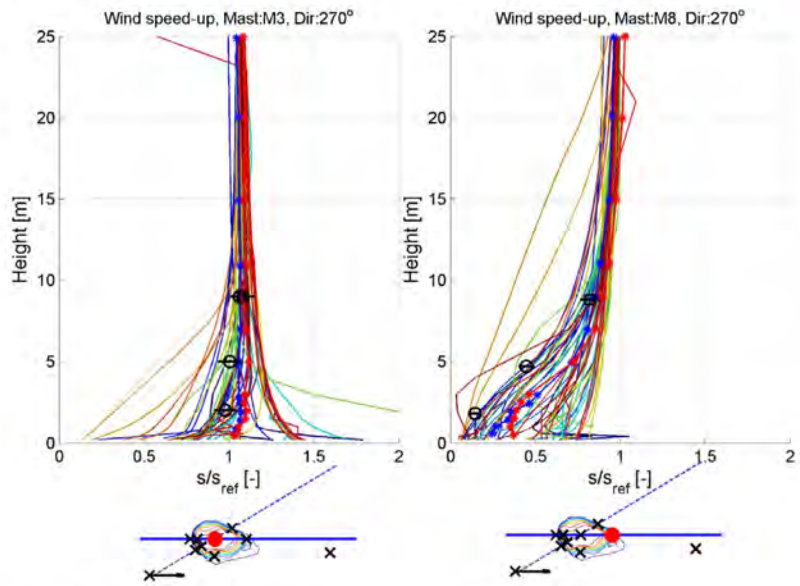
Results: Speed-up



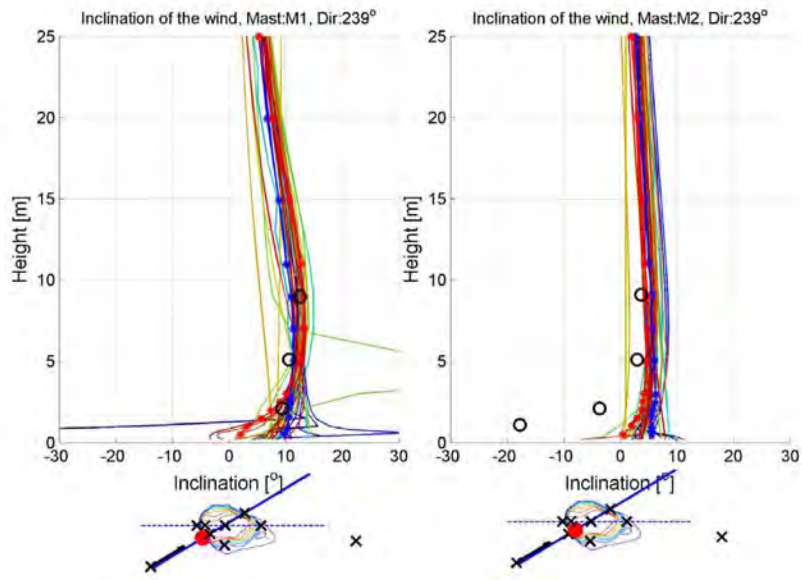
Results: Speed-up



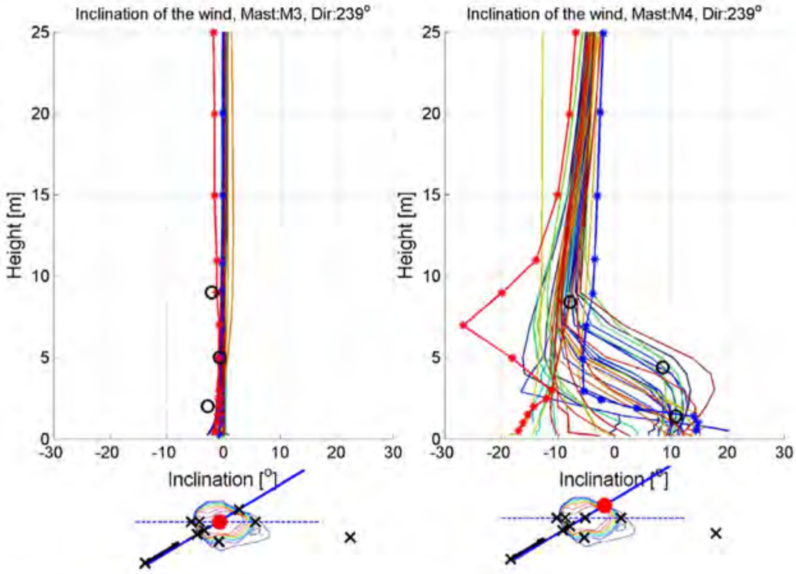
Results: Speed-up



Results

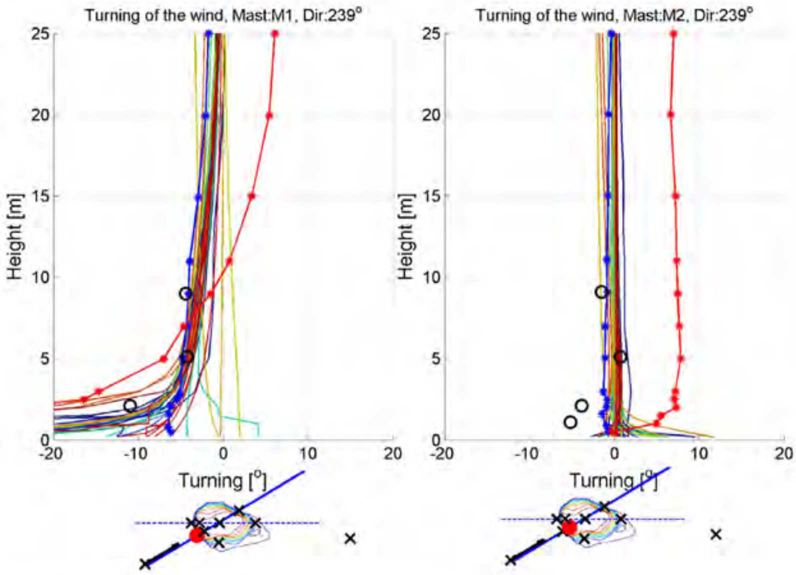


Results



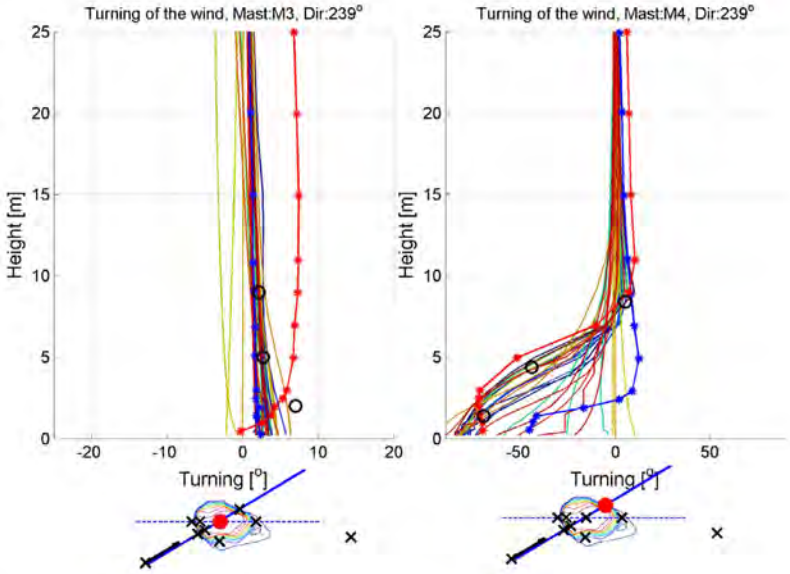
23 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Results



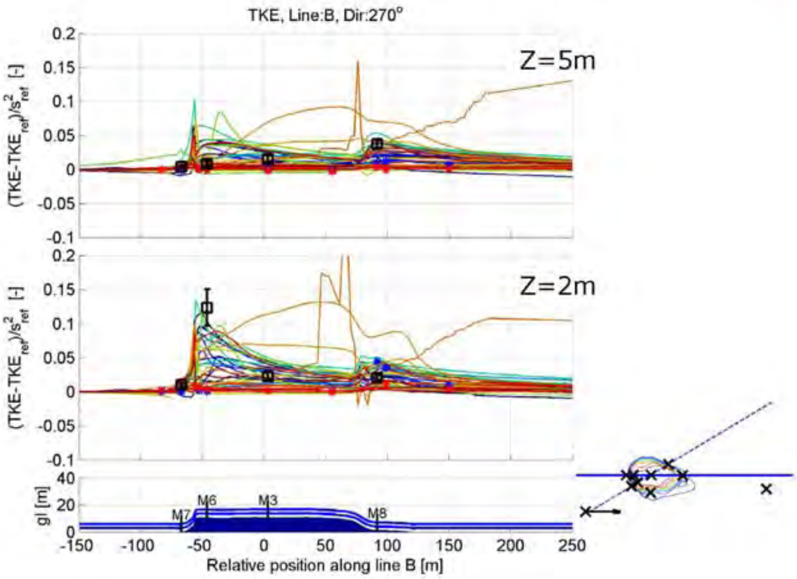
24 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Results

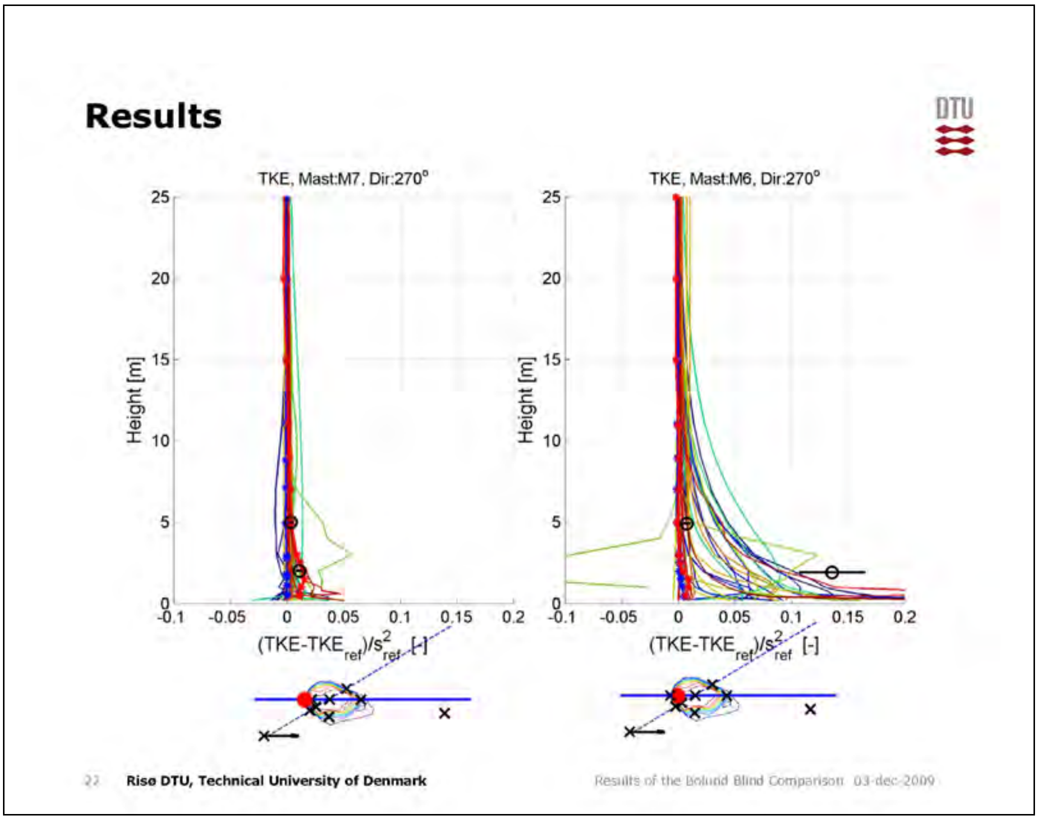


25 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009

Results



26 **Risø DTU, Technical University of Denmark** Results of the Bolund Blind Comparison 03-dec-2009



Results
DTU
TKE, Mast:M7, Dir:270°
TKE, Mast:M6, Dir:270°
Height [m]
(TKE-TKE$_{ref}$)/s$^2_{ref}$ [-]
22
Risø DTU, Technical University of Denmark
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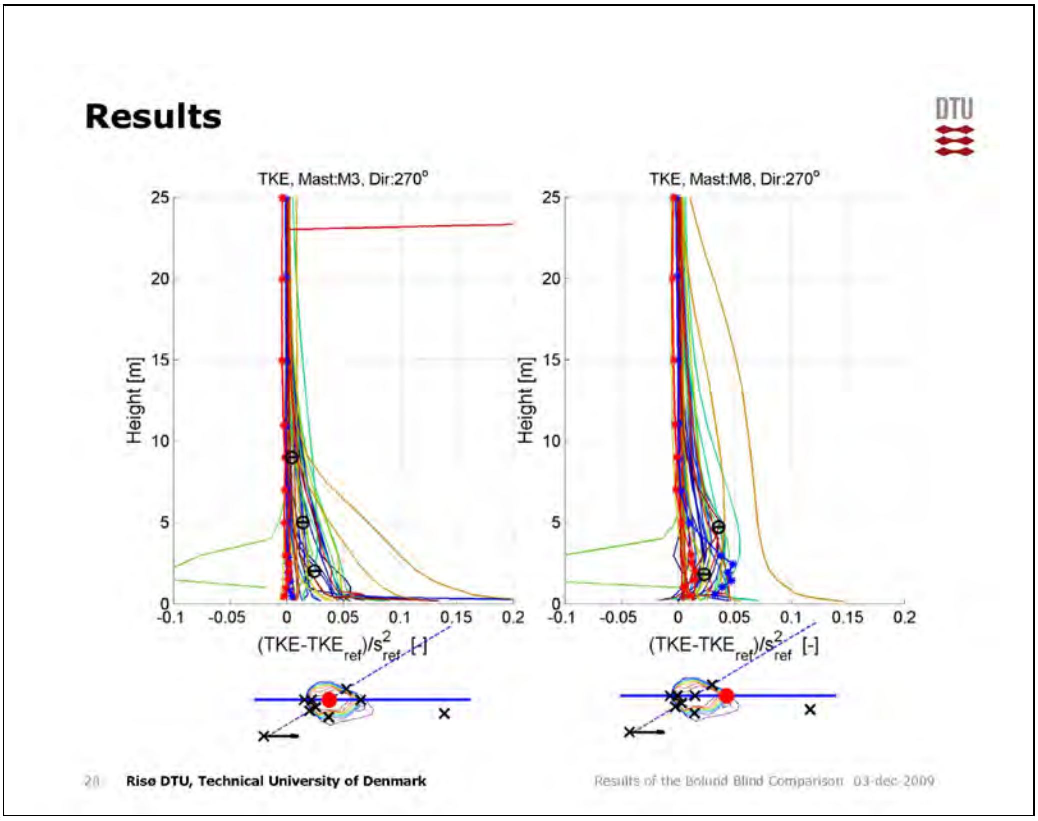


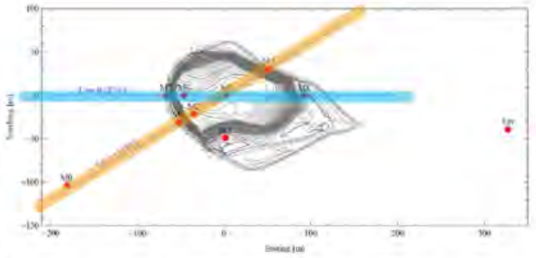
Results
DTU
TKE, Mast:M3, Dir:270°
TKE, Mast:M8, Dir:270°
Height [m]
(TKE-TKE$_{ref}$)/s$^2_{ref}$ [-]
28
Risø DTU, Technical University of Denmark
Results of the Bolund Blind Comparison 03-dec-2009

ERROR

- The averaged error in velocity for line A and B (TPWind: 3%)

@ 2m above ground = 35%
@ 5m above ground = 17%

Mean Error: 26%



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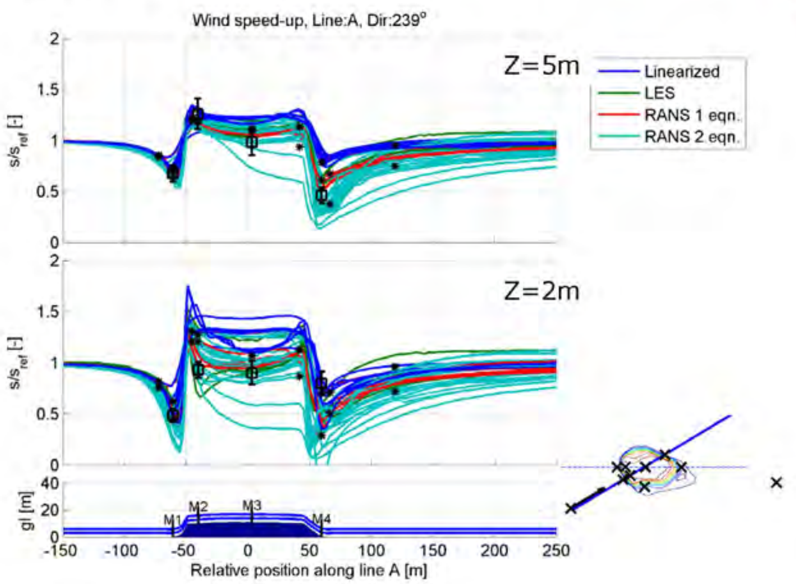
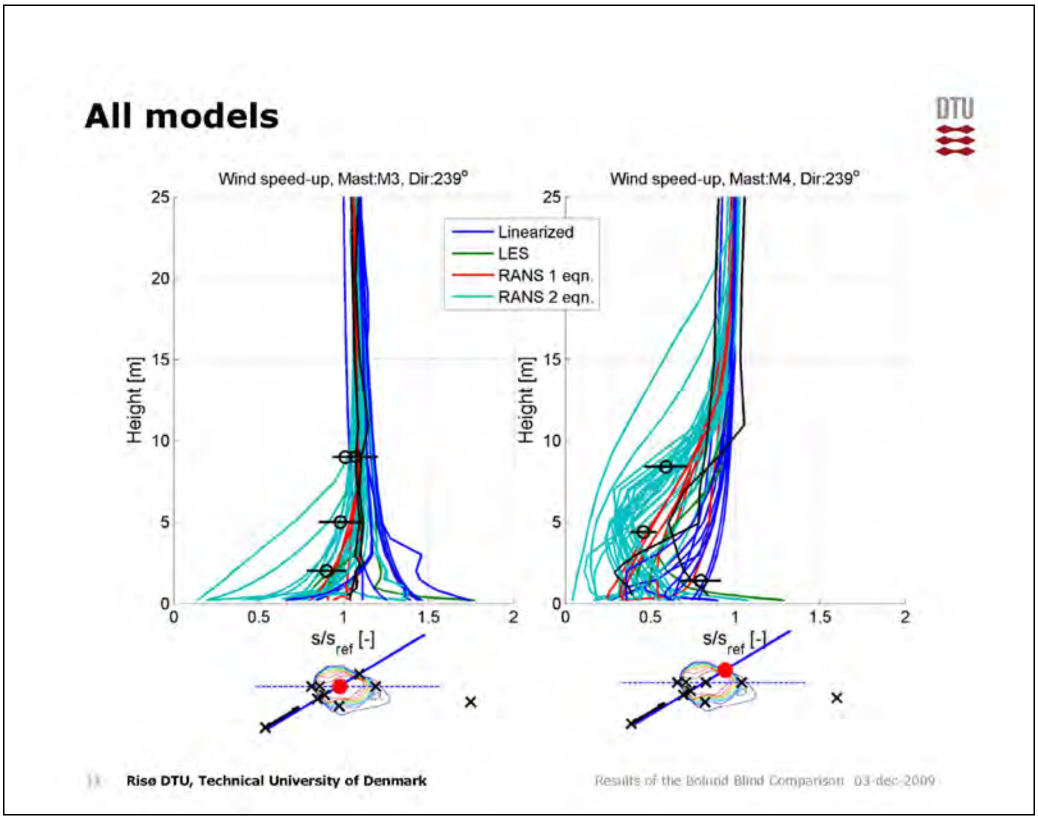
Analysis

Model types:

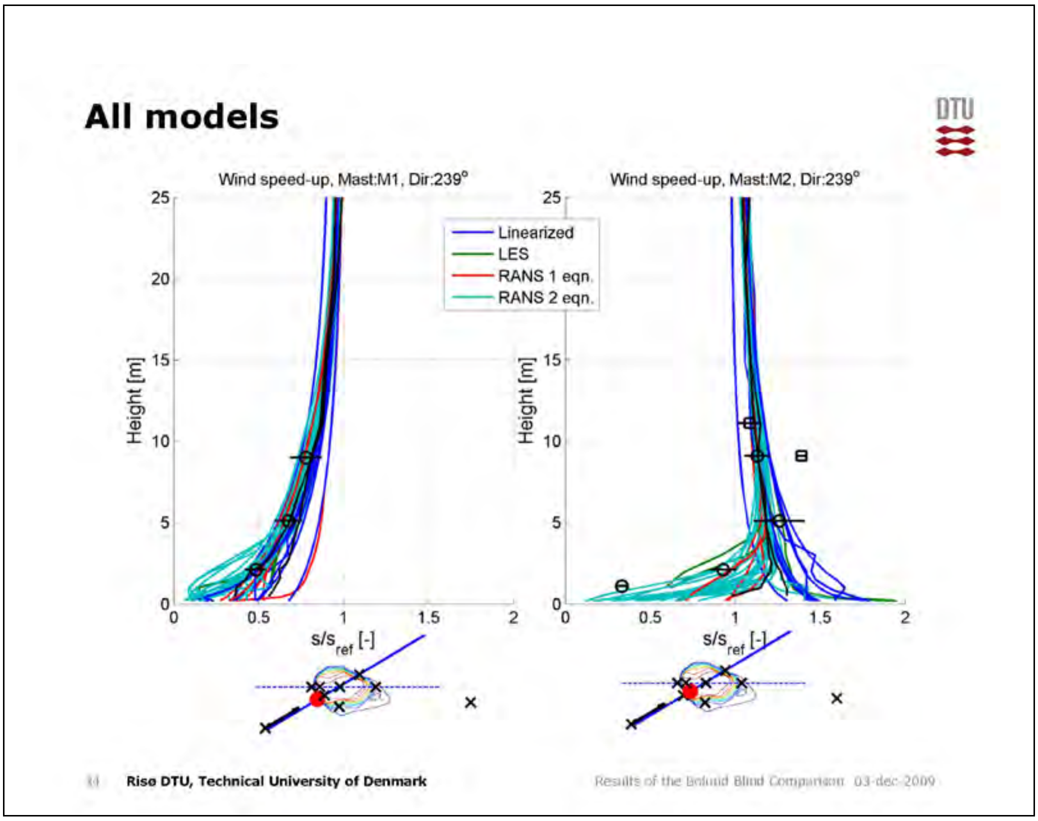
1. Experimental method
2. Linearized flow model
3. LES
4. RANS 1 eq.
5. RANS 2 eq.

All models

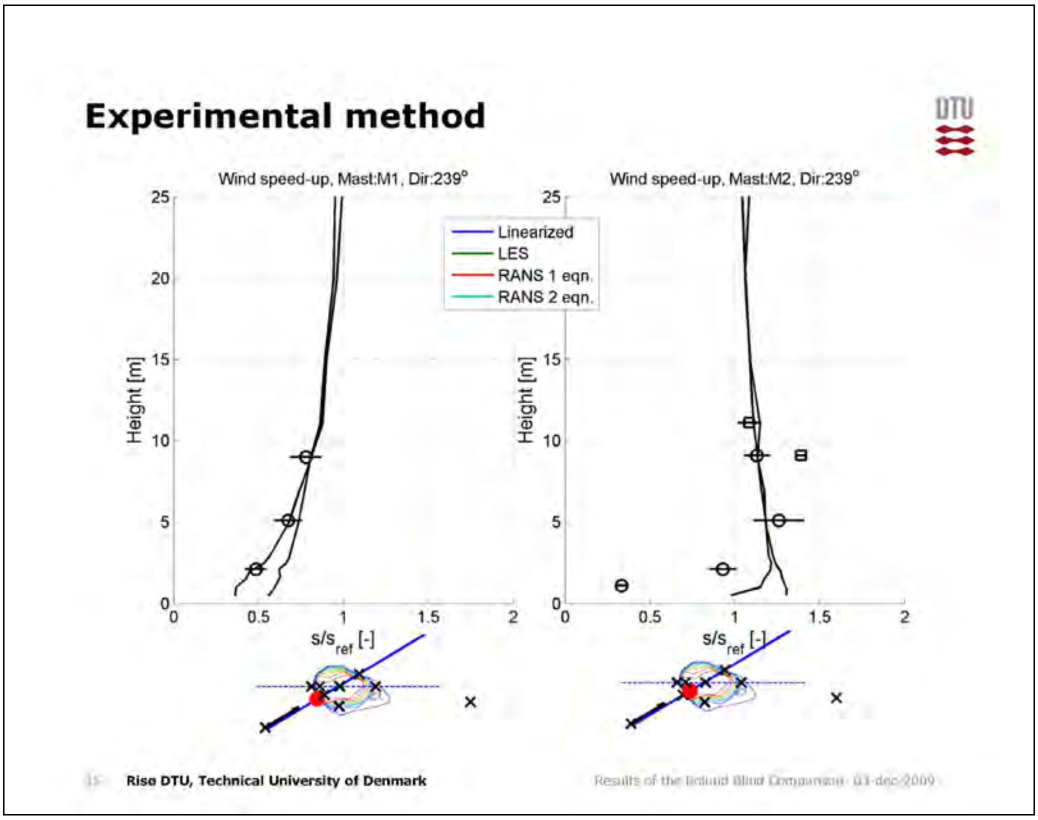


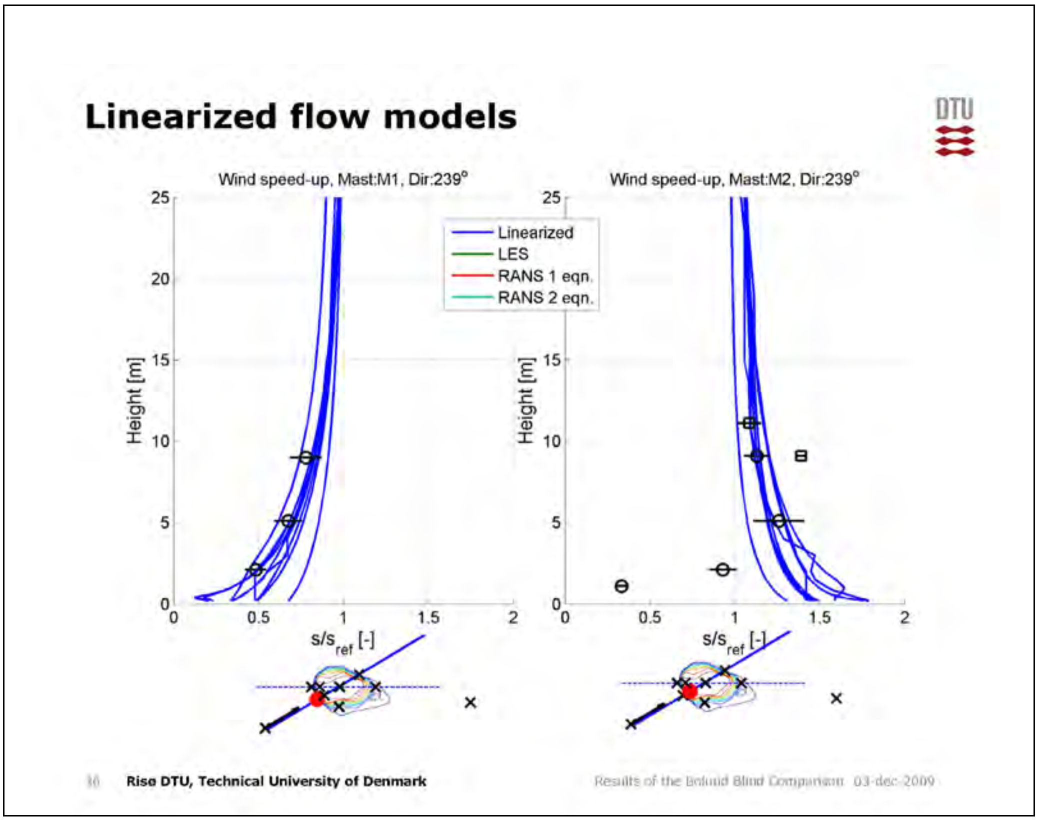


All models
DTU
Wind speed-up, Mast:M3, Dir:239°
Wind speed-up, Mast:M4, Dir:239°
Linearized
LES
RANS 1 eqn.
RANS 2 eqn.
Height [m]
s/s_ref [-]
Risø DTU, Technical University of Denmark
Results of the Bolund Blind Comparison 03-dec-2009

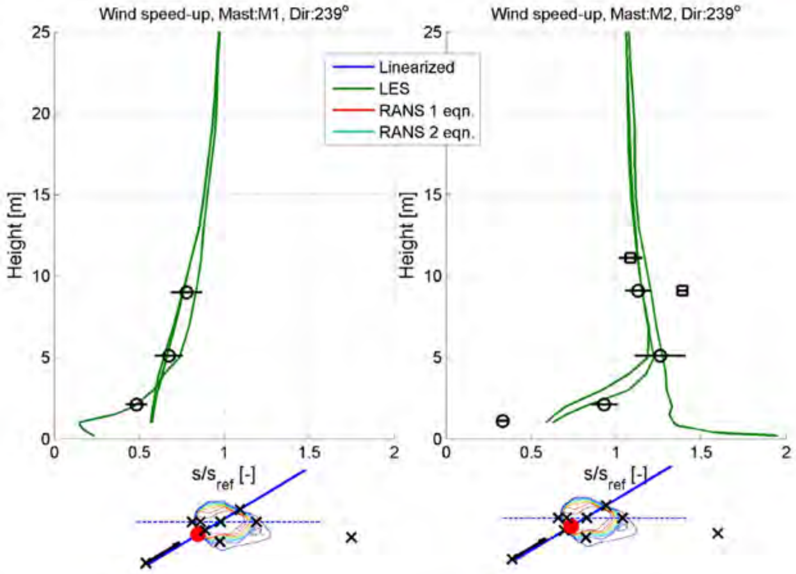


All models
DTU
Wind speed-up, Mast:M1, Dir:239°
Wind speed-up, Mast:M2, Dir:239°
Linearized
LES
RANS 1 eqn.
RANS 2 eqn.
Height [m]
s/s_ref [-]
Risø DTU, Technical University of Denmark
Results of the Bolund Blind Comparison 03-dec-2009


Experimental method
Wind speed-up, Mast:M1, Dir:239°
Wind speed-up, Mast:M2, Dir:239°
Linearized
LES
RANS 1 eqn.
RANS 2 eqn.
Height [m]
s/s_ref [-]
Risø DTU, Technical University of Denmark
Results of the Bolund Blind Comparison 03-dec-2009


Linearized flow models
Wind speed-up, Mast:M1, Dir:239°
Wind speed-up, Mast:M2, Dir:239°
Linearized
LES
RANS 1 eqn.
RANS 2 eqn.
Height [m]
s/s_ref [-]
Risø DTU, Technical University of Denmark
Results of the Bolund Blind Comparison 03-dec-2009

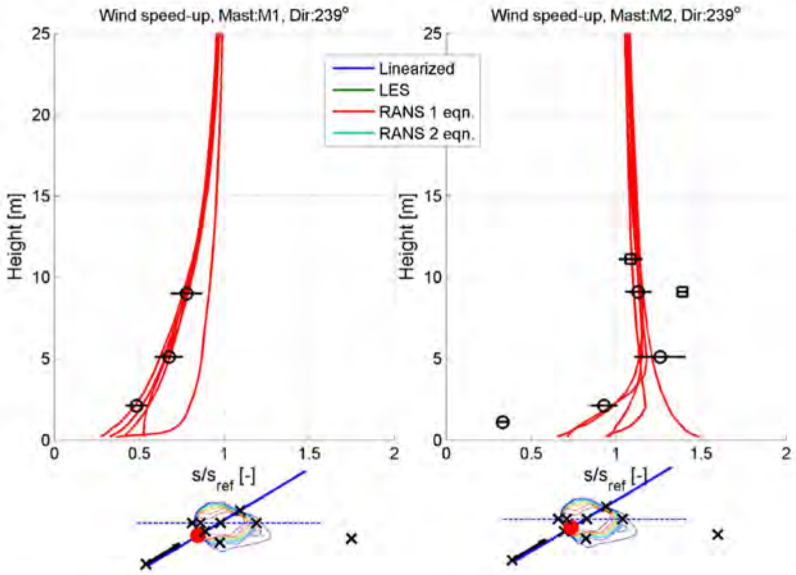
LES models



Risø DTU, Technical University of Denmark

Results of the Bolund Blind Comparison 03-dec-2009

RANS 1 eq. models



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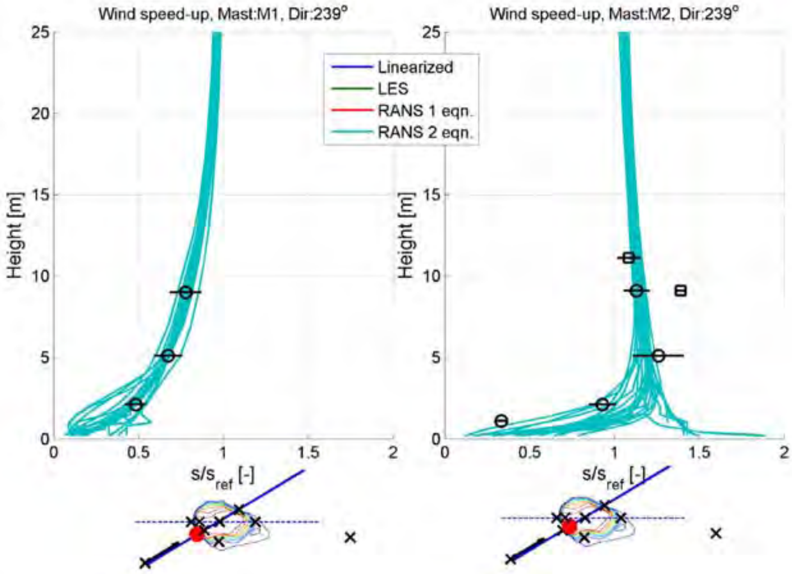
Results of the Bolund Blind Comparison 03-dec-2009

RANS 2 eq. models



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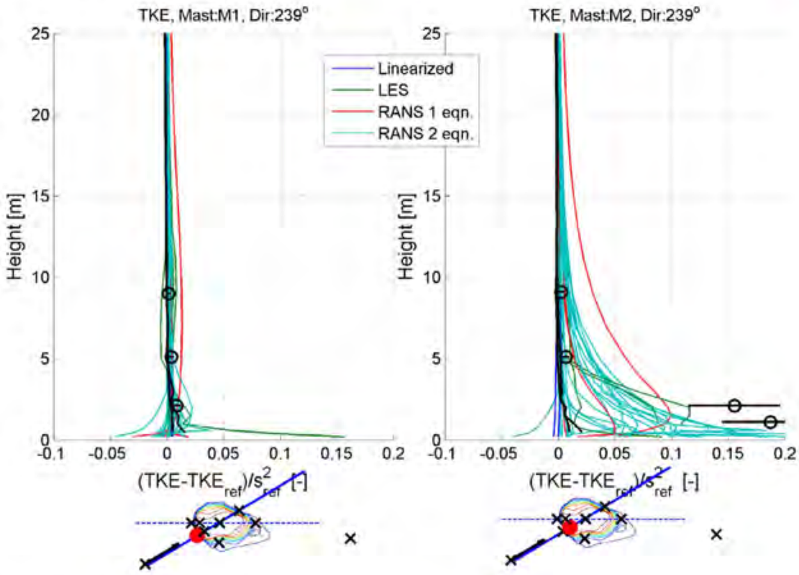
Results of the Bolund Blind Comparison 03-dec-2009

All models



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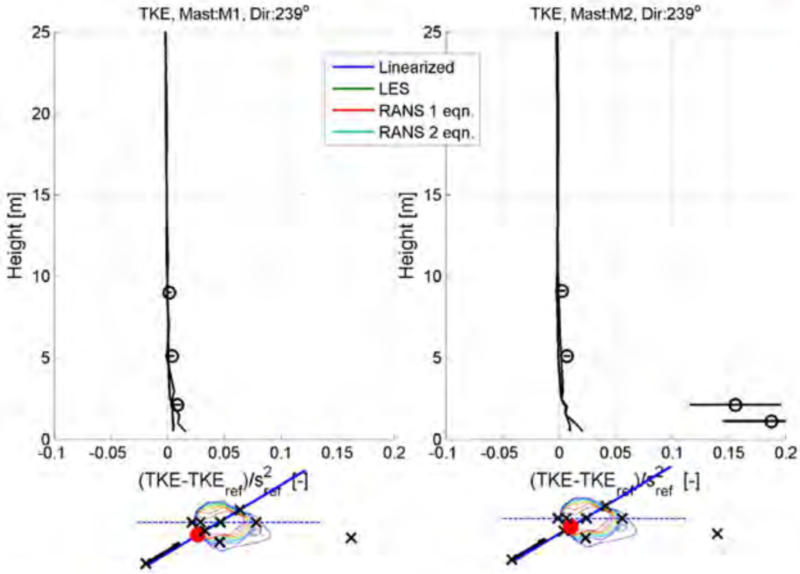
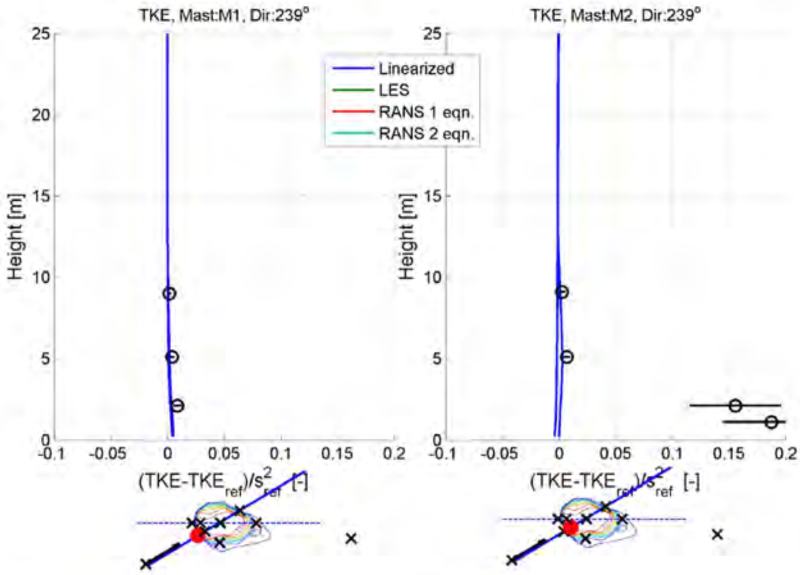
Results of the Bolund Blind Comparison 03-dec-2009

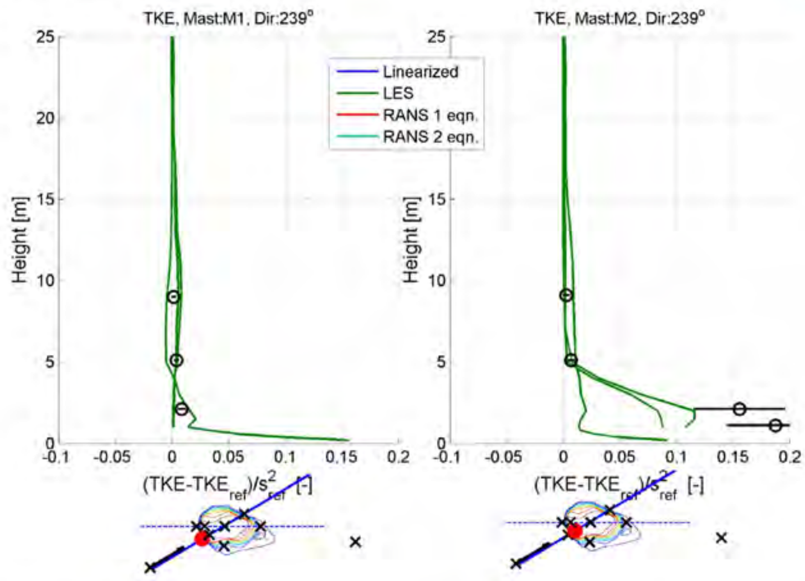
Experimental method



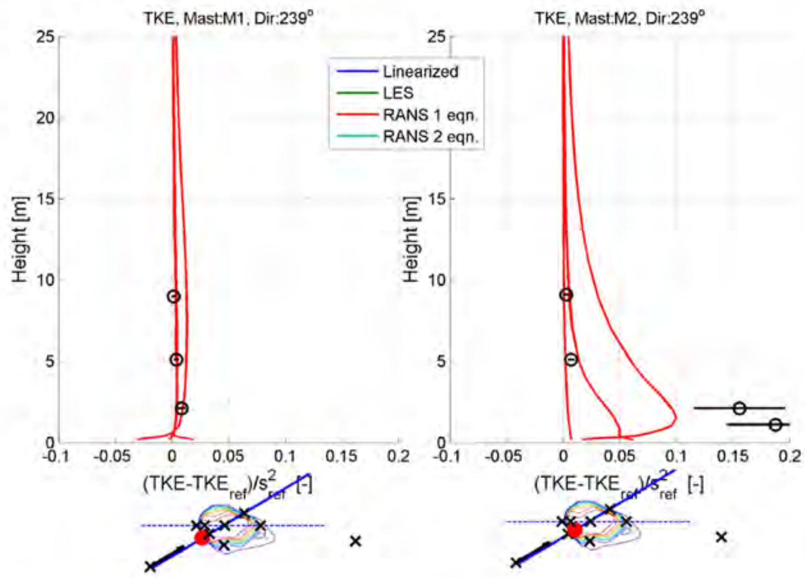
Linearized flow models



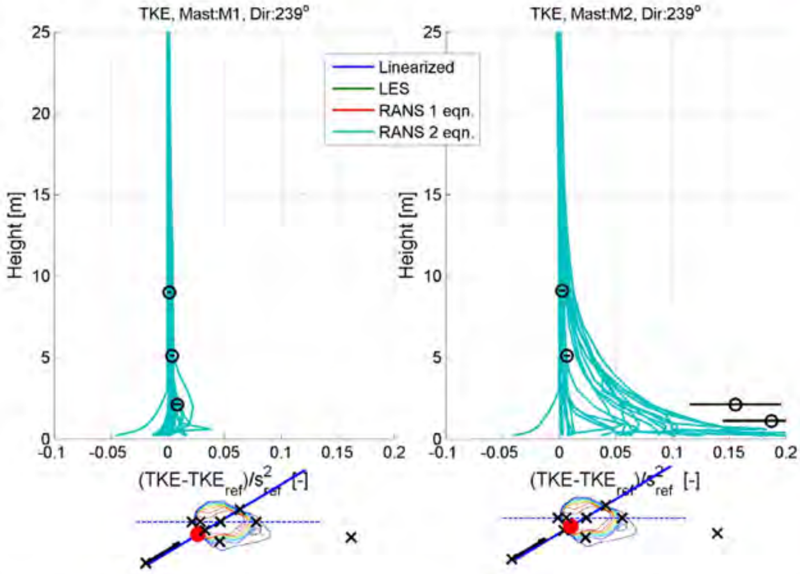
LES models



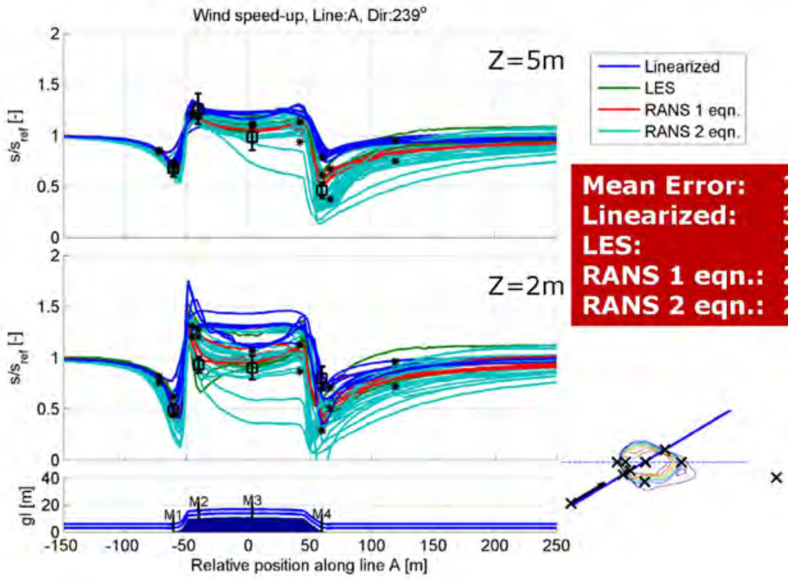
RANS 1 eq. models



RANS 2 eq. models

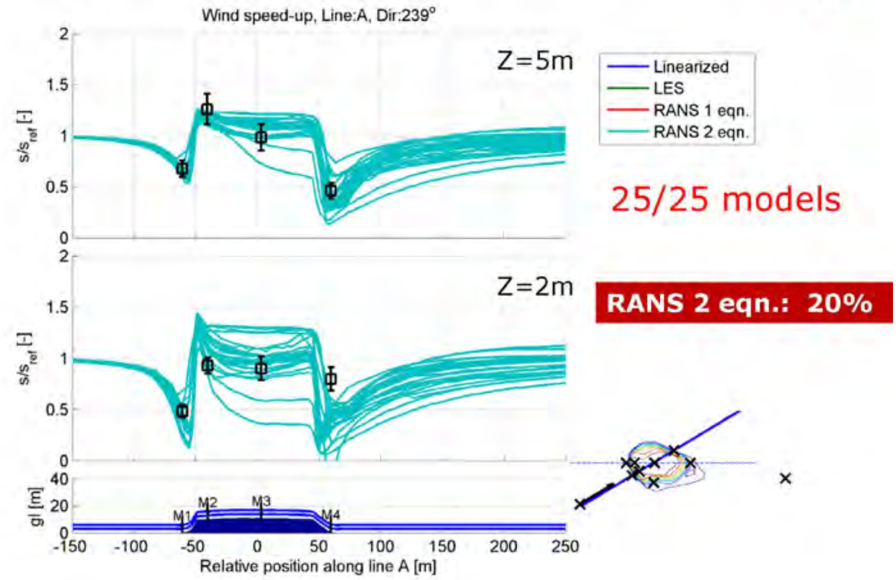


All models

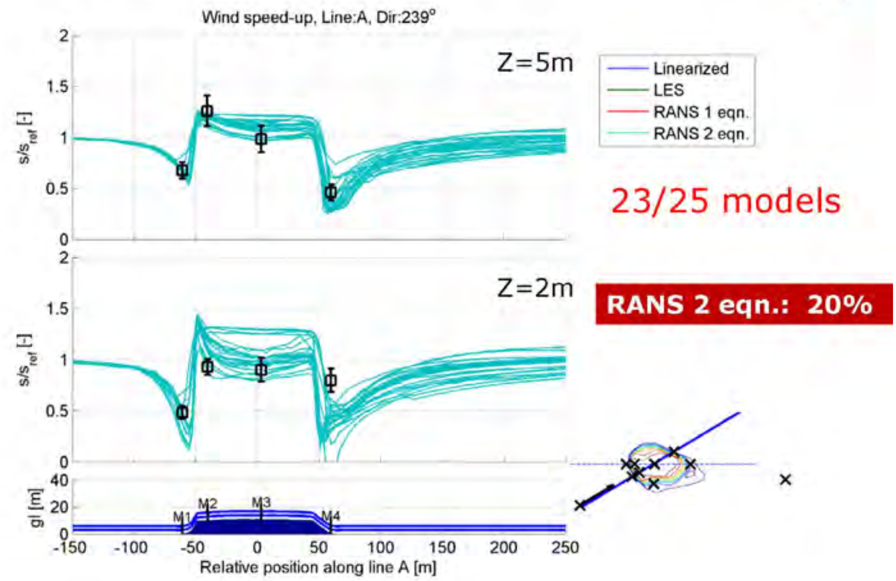


Mean Error: 26%
Linearized: 35%
LES: 26%
RANS 1 eqn.: 25%
RANS 2 eqn.: 20%

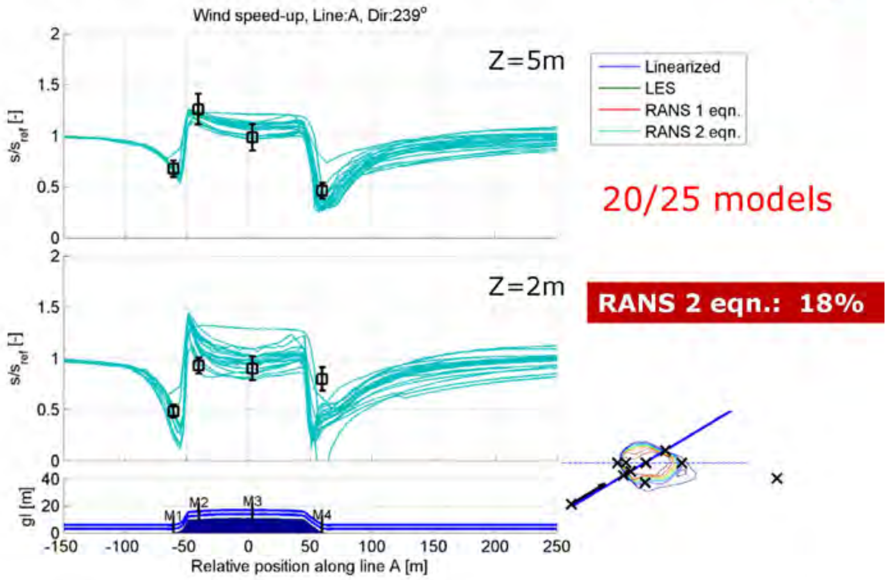
RANS 2 eq. models



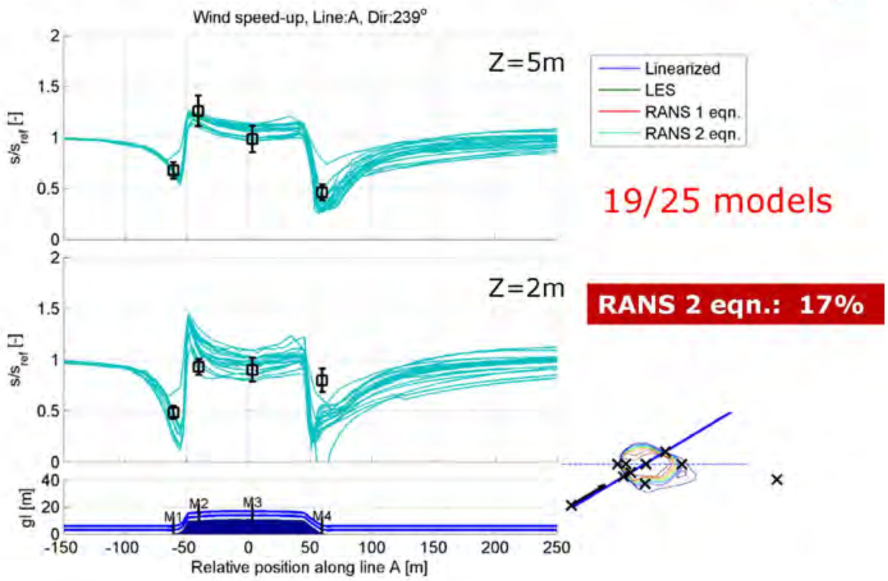
RANS 2 eq. models

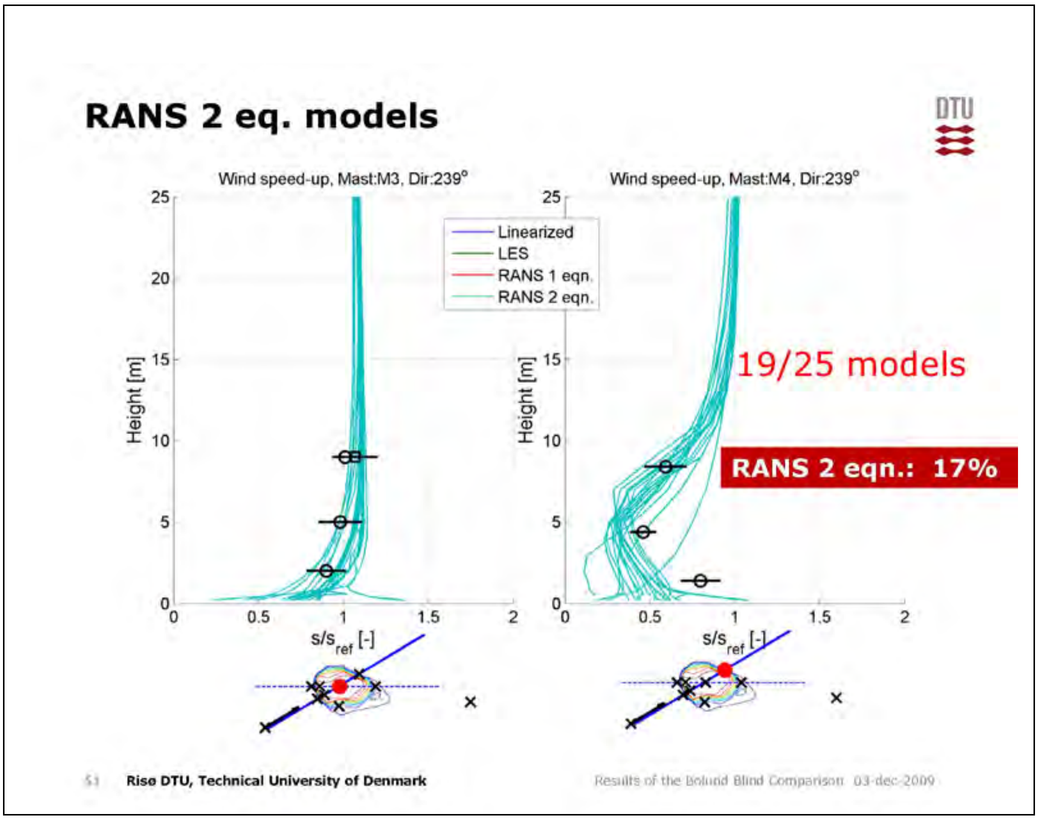


RANS 2 eq. models



RANS 2 eq. models




RANS 2 eq. models
Wind speed-up, Mast:M3, Dir:239°
Wind speed-up, Mast:M4, Dir:239°
Linearized
LES
RANS 1 eqn.
RANS 2 eqn.
Height [m]
s/s_ref [-]
19/25 models
RANS 2 eqn.: 17%
51
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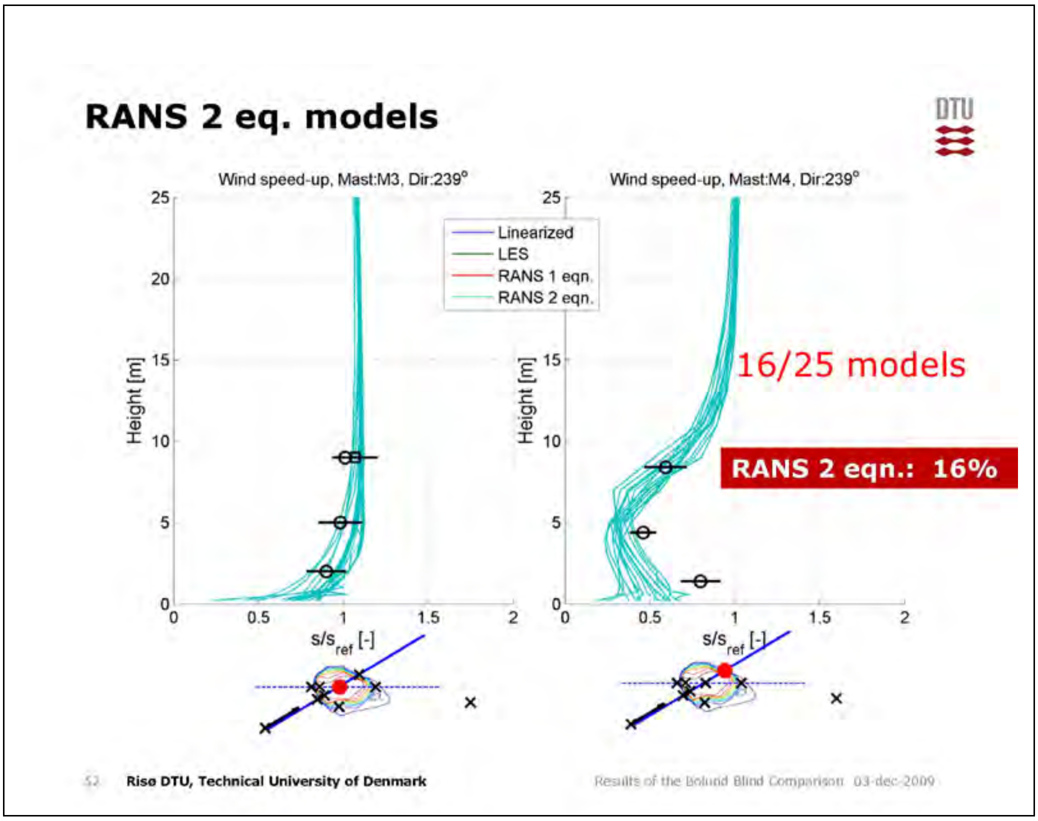
RANS 2 eq. models
Wind speed-up, Mast:M3, Dir:239°
Wind speed-up, Mast:M4, Dir:239°
Linearized
LES
RANS 1 eqn.
RANS 2 eqn.
Height [m]
s/s_ref [-]
16/25 models
RANS 2 eqn.: 16%
52
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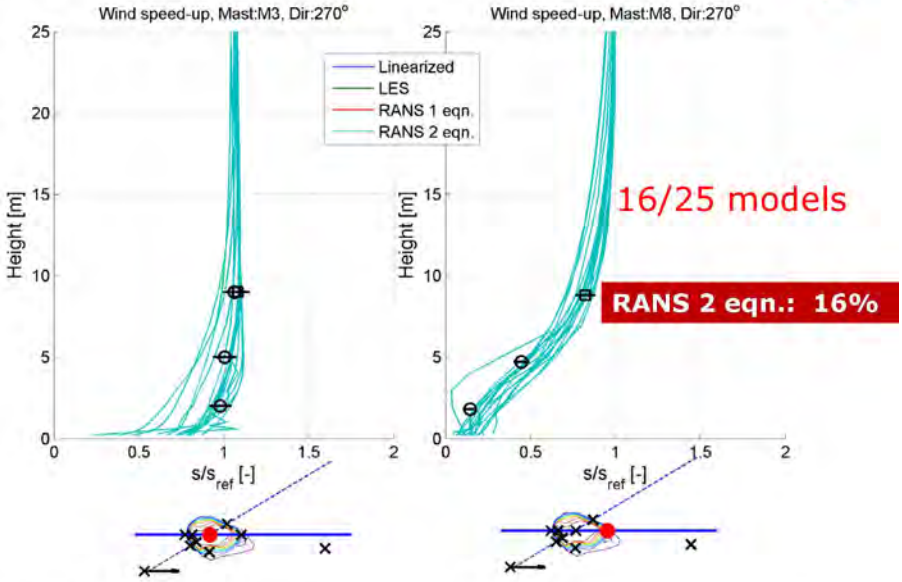
Results of the Bolund Blind Comparison 03-dec-2009

RANS 2 eq. models



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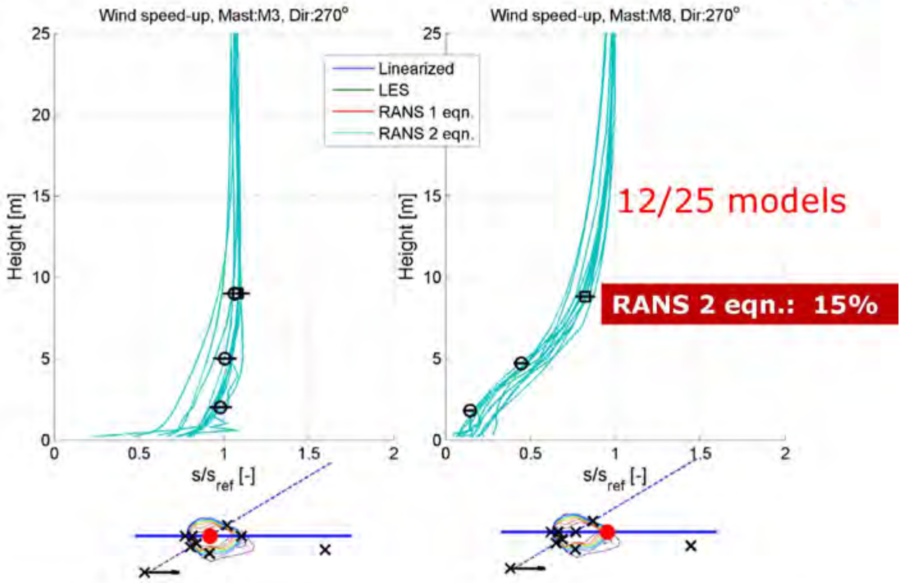
RANS 2 eq. models



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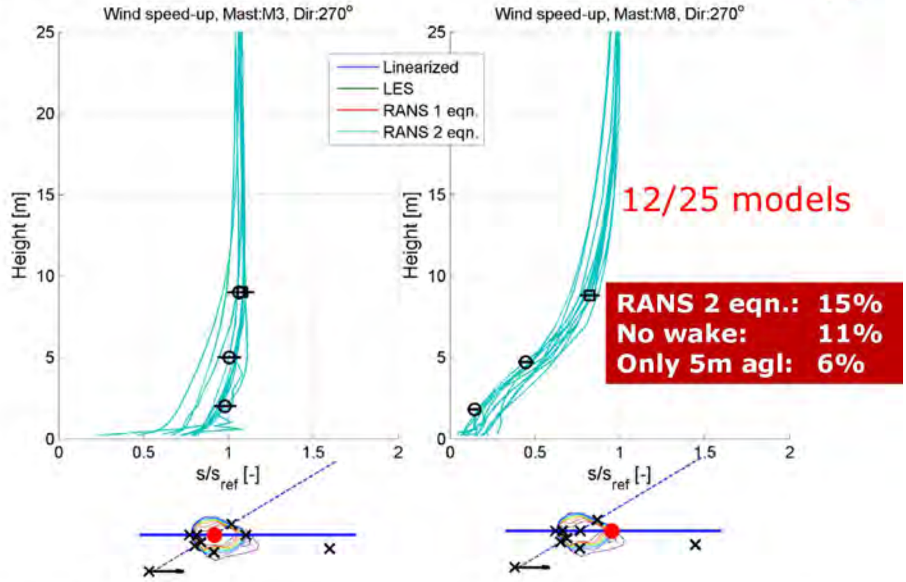
RANS 2 eq. models



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Top 10 List

ID	Turb. model	Error [%]	Error 5m [%]
ID0053	RANS k-epsilon	13	6
ID0037	RANS k-epsilon	14	4
ID0000	RANS k-epsilon	14	5
ID0036	RANS k-epsilon	14	5
ID0016	RANS k-epsilon	14	5
ID0015	RANS k-epsilon	15	5
ID0077	RANS k-epsilon	15	5
ID0010	RANS k-epsilon	15	7
ID0009	RANS k-epsilon	15	5
ID0034	RANS 1 eqn.	17	7
ID0068	RANS k-epsilon	17	10
ID0006	RANS k-epsilon	17	6

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Content

1. Introduction
2. Measurements & Simulations
3. Results
4. Analysis
5. Conclusions

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Conclusions

Physical models:

- Mean velocity looks well predicted
- TKE is too low

Lin. Models:

- Gave the largest error – not designed for Bolund (90 dir better)
- The peak in speedup was missing and a some spread in model results

LES:

- Many modelers had problems doing LES of Bolund
- The spread was large (not matured but showed potential)

RANS:

- State-of-the-art!
- Many models showed similar trends
- Some RANS simulations seems to be too "coarse" (two trends)

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Conclusions

- TPWind: uncertainty of less than 3% - We have a long way!
- Bolund is an "ideal" case to test flow models. The uncertainty would be larger on "real" WT-sites
- How do you compare measurements and simulations?
- With best practice CFD guides results could probably be improved considerable (eg. Convergence test: results must be grid independent)
- The top 10 list consisted of 7 different CFD solver:
  1. You can get good results with most solvers
  2. The user is more important than the solver
- Recommendation: RANS will be the workhorse for many years to come

- Take a break – look at your results and discuss – make your own conclusions ☺

Thank you

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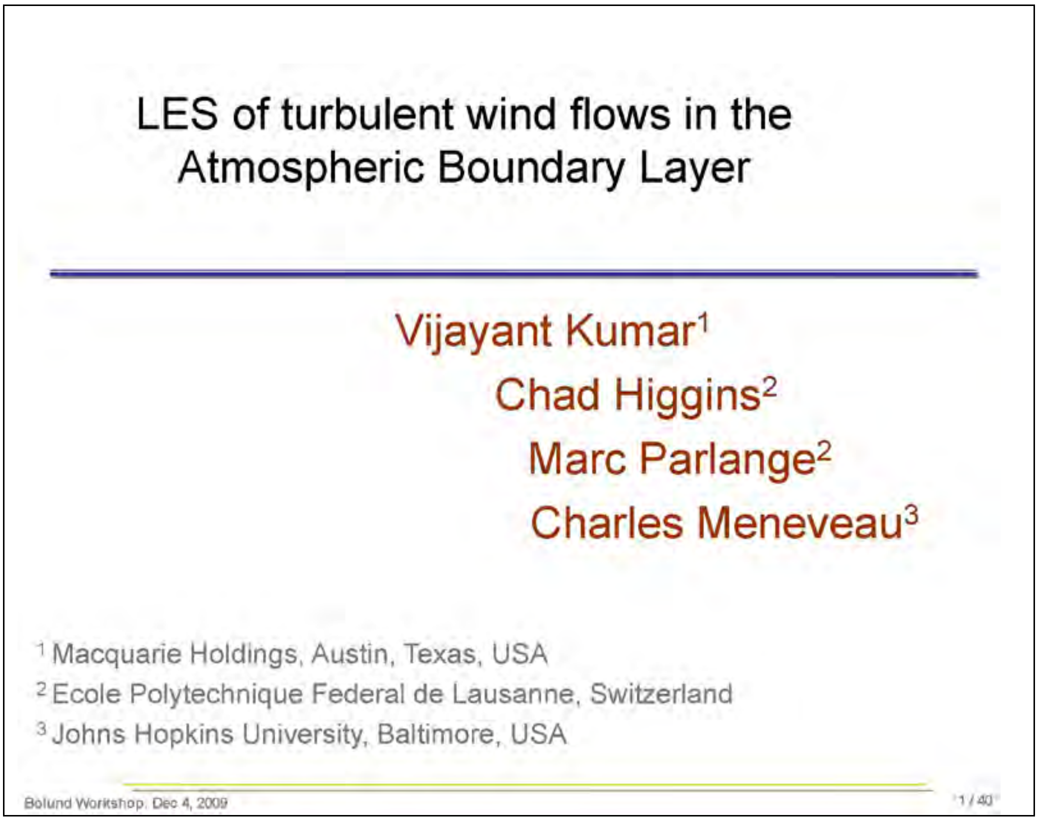
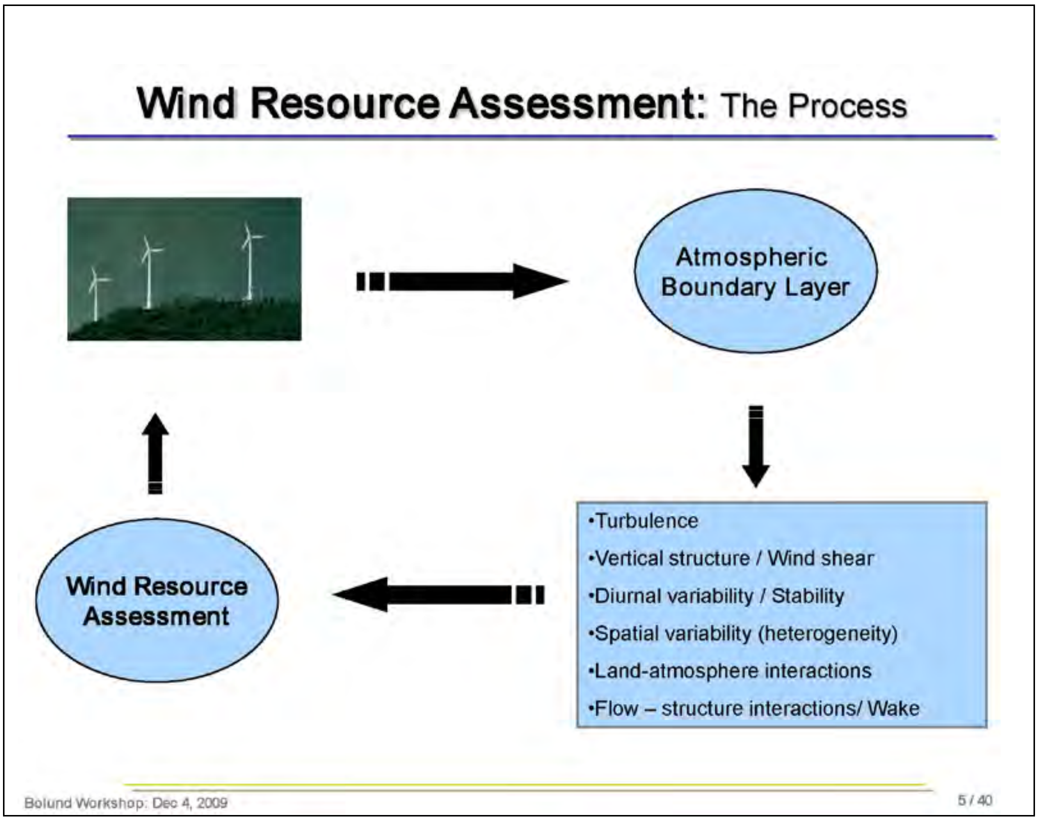
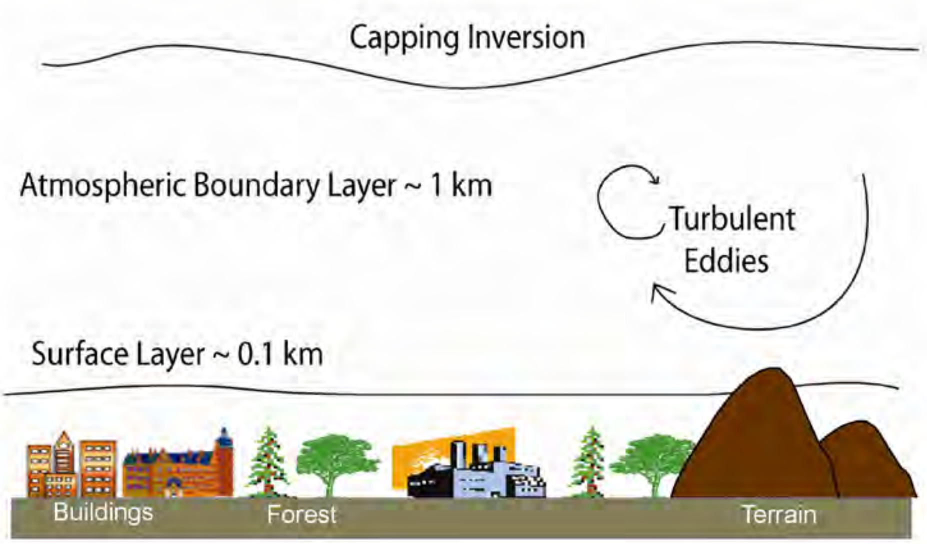
“LES of turbulent wind flows in the Atmospheric Boundary Layer” - by Vijayant Kumar

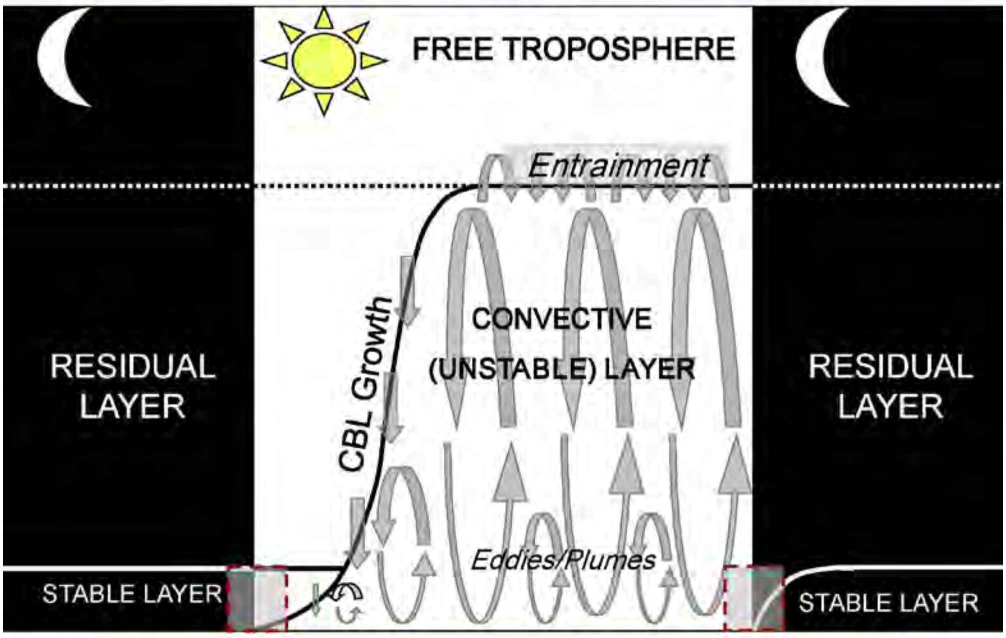


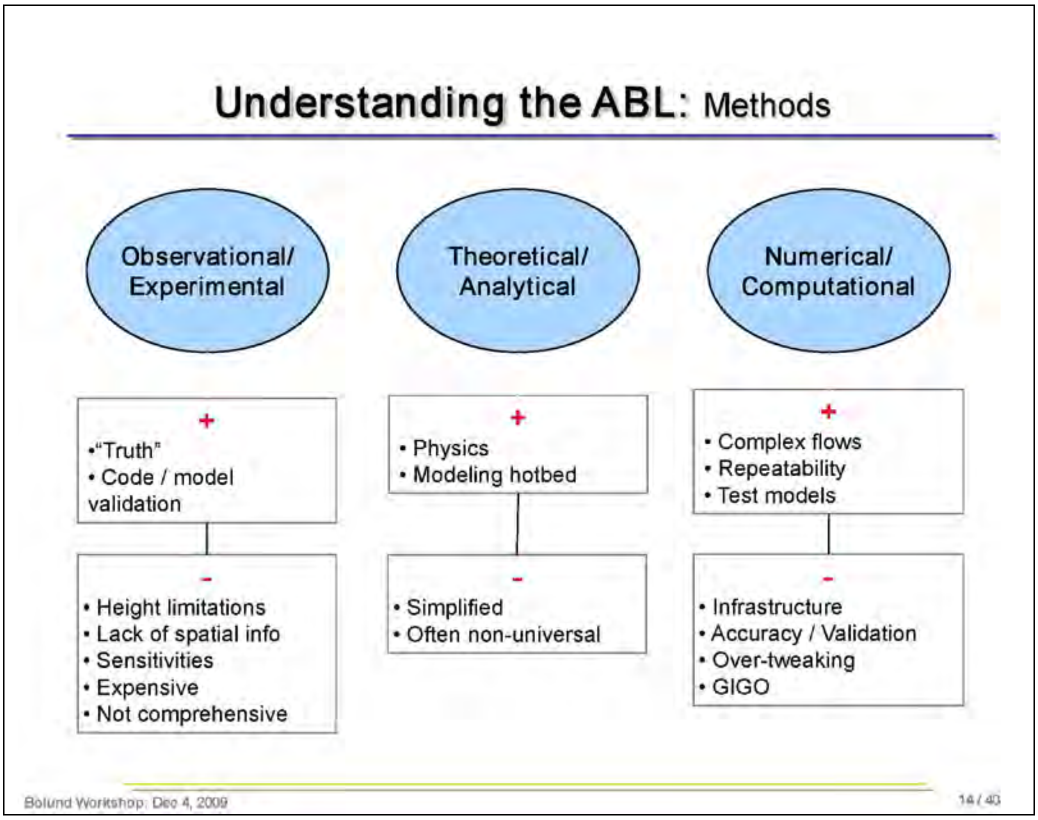


Atmospheric Boundary Layer: Spatial Complexity



Atmospheric Boundary Layer: Temporal Complexity




Understanding the ABL: Methods
Observational/ Experimental
Theoretical/ Analytical
Numerical/ Computational
+
•"Truth"
• Code / model validation
-
• Height limitations
• Lack of spatial info
• Sensitivities
• Expensive
• Not comprehensive
+
• Physics
• Modeling hotbed
-
• Simplified
• Often non-universal
+
• Complex flows
• Repeatability
• Test models
-
• Infrastructure
• Accuracy / Validation
• Over-tweaking
• GIGO
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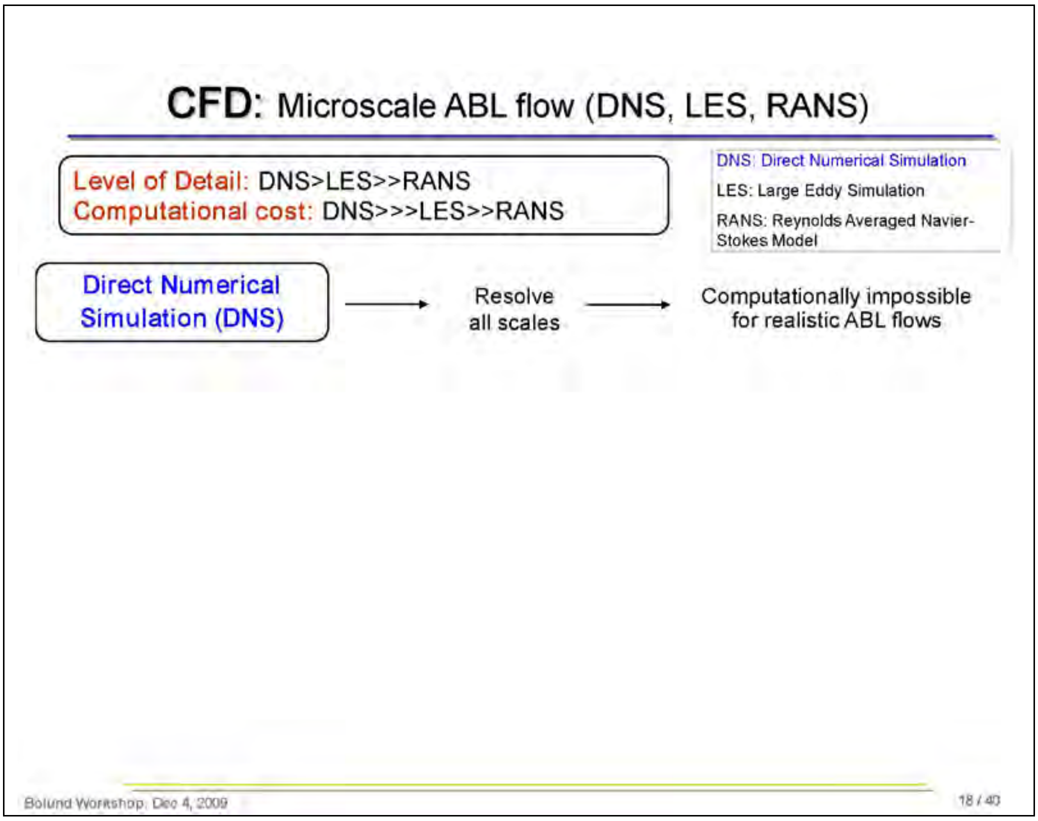
CFD: Microscale ABL flow (DNS, LES, RANS)
Level of Detail: DNS>LES>>RANS
Computational cost: DNS>>>LES>>RANS
DNS: Direct Numerical Simulation
LES: Large Eddy Simulation
RANS: Reynolds Averaged Navier-Stokes Model
Direct Numerical Simulation (DNS)
Resolve all scales
Computationally impossible for realistic ABL flows
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CFD: Microscale ABL flow (DNS, LES, RANS)

Level of Detail: DNS>LES>>RANS
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DNS: Direct Numerical Simulation
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Large Eddy Simulation (LES)

- Predict instantaneous flow characteristics (+)
- A large portion of the turbulence spectrum is completely resolved (+)
- Represent complex flow regimes such as separation, wakes, stability transitions & stable boundary layers (+)
- Subgrid scale models can be universally applied (+)
- High computational cost: Parallel (-)
- Quality of results = $f(\text{user})$ => GIGO (-)

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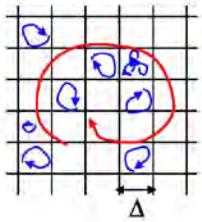
Large Eddy Simulation (LES)

Incompressible Navier-Stokes, Re ~ 10^8

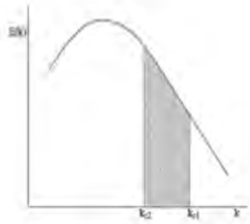


Filtering

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial(\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + g\left(\frac{\tilde{\theta}-\tilde{\theta}_0}{\tilde{\theta}_0}\right)\delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - V_g)\delta_{i1} - f(\tilde{u}_1 - U_g)\delta_{i2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j}$$



$$\boxed{\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j \qquad \pi_{ij} = \widetilde{u_i \theta} - \tilde{u}_i \tilde{\theta}}$$

Subgrid scale modeling

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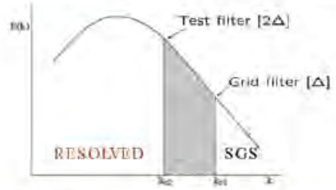
LES: SGS Modeling

$$\tau_{ij} = -2\nu_t \tilde{S}_{ij};\ \pi_j = -\frac{\nu_t}{Pr_{sgs}}\frac{\partial \tilde{\theta}}{\partial x_j};\ \nu_t = (C_{s,\Delta}\Delta)^2|\tilde{S}_{ij}|;\ \tilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)$$

Eddy Viscosity (ν_t) type models:

Static Smagorinsky	Dynamic Model
Constant value $C_{s,\Delta}$ imposed everywhere	• $C_{s,\Delta}$ determined dynamically from the resolved scales • $C_{s,\Delta}$ is spatially averaged



CFD: Microscale ABL flow (DNS, LES, RANS)

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Direct Numerical Simulation (DNS) → Resolve all scales → Computationally impossible for realistic ABL flows

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Direct Numerical Simulation (DNS)

Large Eddy Simulation (LES)

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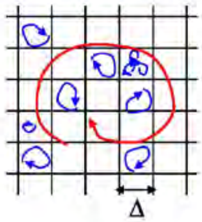

Filtering

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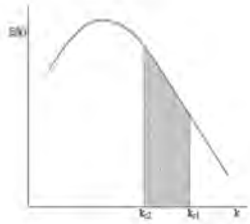
$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial(\tilde{u}_i \tilde{u}_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i} + g\left(\frac{\tilde{\theta} - \tilde{\theta}_0}{\tilde{\theta}_0}\right)\delta_{i3} - \frac{\partial \tau_{ij}}{\partial x_j} + f(\tilde{u}_2 - V_g)\delta_{i1} - f(\tilde{u}_1 - U_g)\delta_{i2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial \pi_j}{\partial x_j}$$

$$\boxed{\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j \qquad \pi_{ij} = \widetilde{u_i \theta} - \tilde{u}_i \tilde{\theta}}$$



Subgrid scale modeling

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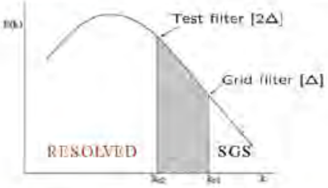
Eddy Viscosity (ν_t) type models:

Static Smagorinsky	Dynamic Model
Constant value $C_{s,\Delta}$ imposed everywhere	• $C_{s,\Delta}$ determined dynamically from the resolved scales • $C_{s,\Delta}$ is spatially averaged

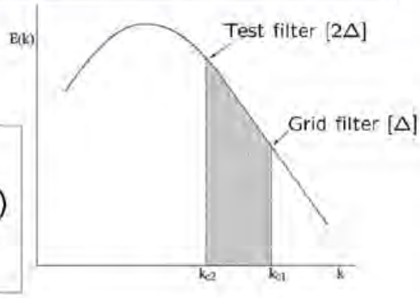


Dynamic SGS model formulation

$$\tau_{ij}^{\Delta} = \widetilde{u_i u_j} - \tilde{u}_i\tilde{u}_j$$

$$\tau_{ij}^{\Delta,m} = -2(C_{s,\Delta}\Delta)^2|\tilde{S}_{ij}|\tilde{S}_{ij}$$

$$\boxed{\begin{aligned} L_{ij} &= T_{ij} - \hat{\tau}_{ij} \\ &= \widehat{\widetilde{u_i u_j}} - \hat{\tilde{u}}_i\hat{\tilde{u}}_j - (\widehat{\widetilde{u_i u_j}} - \widehat{\tilde{u}_i\tilde{u}_j}) \\ &= \widehat{\tilde{u}_i\tilde{u}_j} - \hat{\tilde{u}}_i\hat{\tilde{u}}_j \end{aligned}}$$



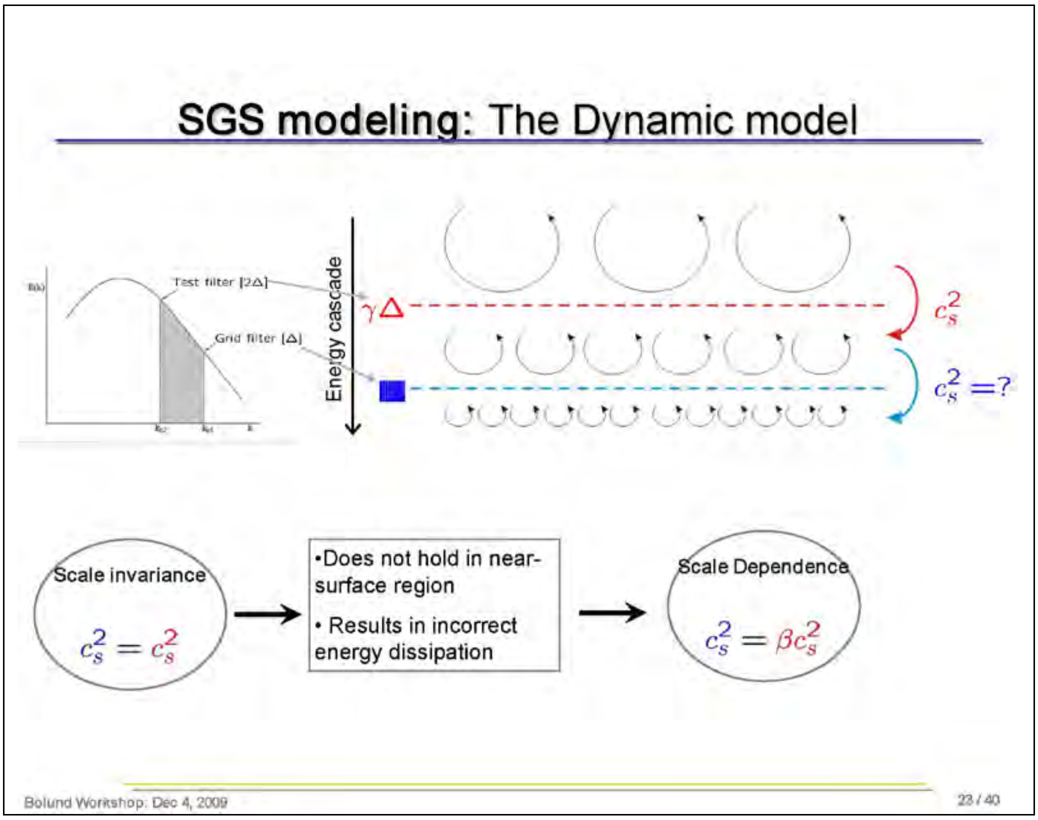
$$L_{ij}^m = T_{ij}^m - \widehat{\tau_{ij}^m}$$

Assume scale invariance $\longrightarrow$ $\boxed{C_{s,2\Delta} = C_{s,\Delta}}$

$$L_{ij}^m = C_{s,\Delta}^2 M_{ij};\ M_{ij} = 2(\Delta)^2\widehat{|\tilde{S}|\tilde{S}_{ij}} - 2(2\Delta)^2|\hat{\tilde{S}}|\hat{\tilde{S}}_{ij}$$

$$e_{ij} = L_{ij} - L_{ij}^m = L_{ij} - C_{s,\Delta}^2 M_{ij}$$

Minimize e_{ij} $\longrightarrow$ $\boxed{C_{s,\Delta}^2 = \frac{\langle L_{ij}^m M_{ij}\rangle}{\langle Mij M_{ij}\rangle}}$


SGS modeling: The Dynamic model
Test filter [2Δ]
Grid filter [Δ]
Energy cascade
$\gamma\Delta$
c_s^2
$c_s^2 = ?$
Scale invariance
$c_s^2 = c_s^2$
•Does not hold in near-surface region
• Results in incorrect energy dissipation
Scale Dependence
$c_s^2 = \beta c_s^2$
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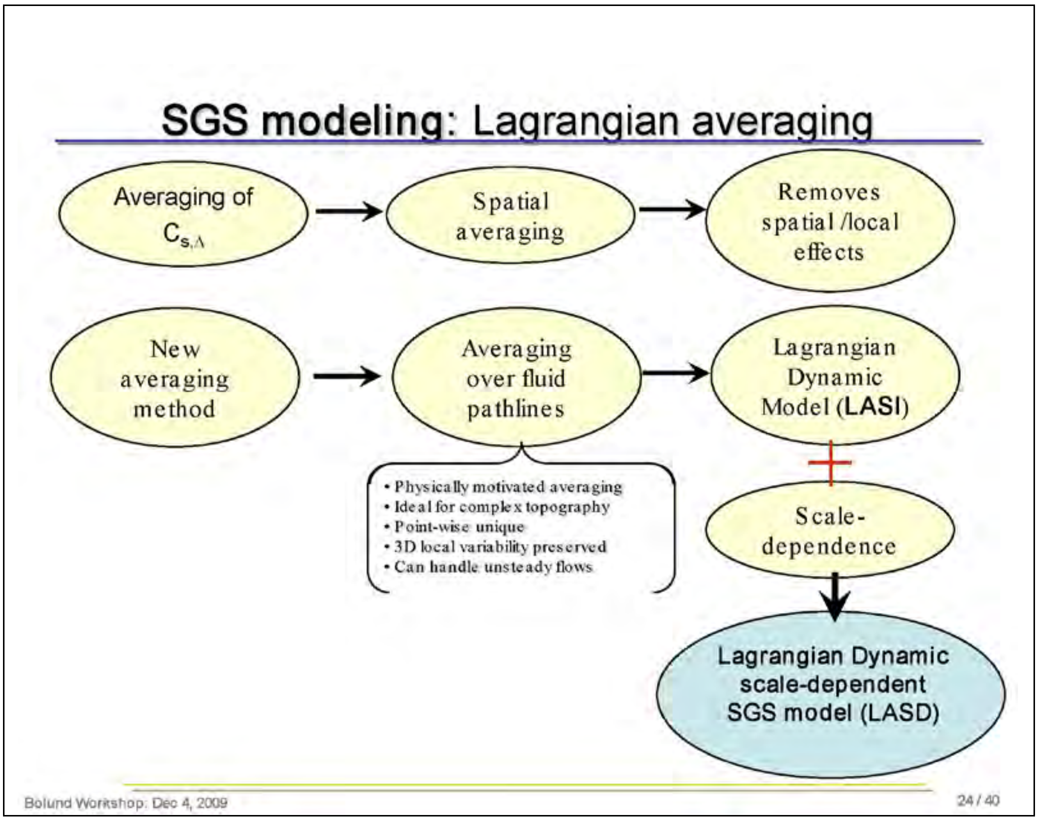
SGS modeling: Lagrangian averaging
Averaging of $C_{s,\Delta}$
Spatial averaging
Removes spatial /local effects
New averaging method
Averaging over fluid pathlines
Lagrangian Dynamic Model (LASI)
• Physically motivated averaging
• Ideal for complex topography
• Point-wise unique
• 3D local variability preserved
• Can handle unsteady flows
Scale-dependence
Lagrangian Dynamic scale-dependent SGS model (LASD)
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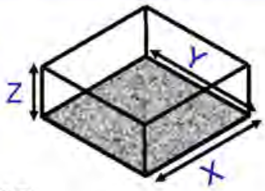
LES code



- Modular Fortran 90/95
- Parallel with FFTW solver
  - Independently verified to be the most efficient parallel code on the NCAR supercomputing clusters
- Lagrangian scale-invariant (LASI) and scale-dependent (LASD) SGS models
- Stability effects => Potential Temperature, Humidity
  - Surface boundary conditions : **Flux** or **Temperature**
- Derivatives: Pseudo-spectral (x,y), finite difference (z)
- Pressure forcing: Geostrophic wind (U_g,V_g)
- Terrain: Level set method, Immersed boundary method

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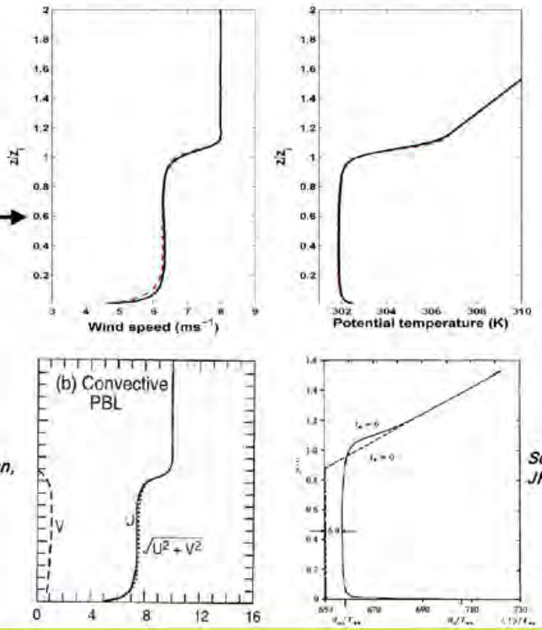
LES of Unstable ABL

Good agreement:
"Large structures"



Moeng and Sullivan, JAS, 1994

Schmidt and Schumann, JFM, 1989

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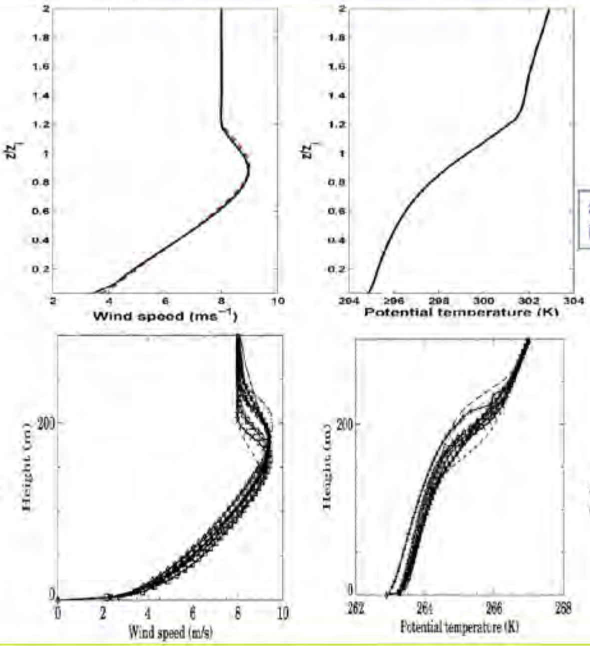
LES of Nocturnal Stable ABL



SGS models become important

Beare et al., BLM, 2006

Beare et al., BLM, 2006

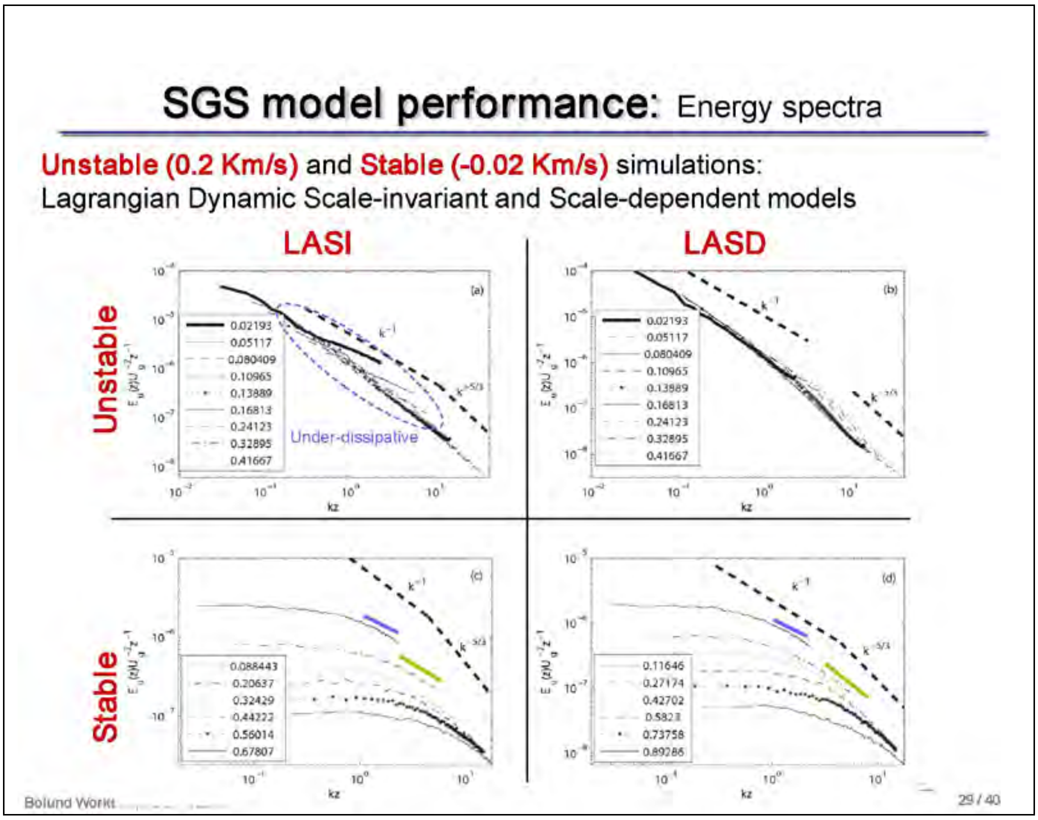
LES of Quasi-steady ABLs: A review

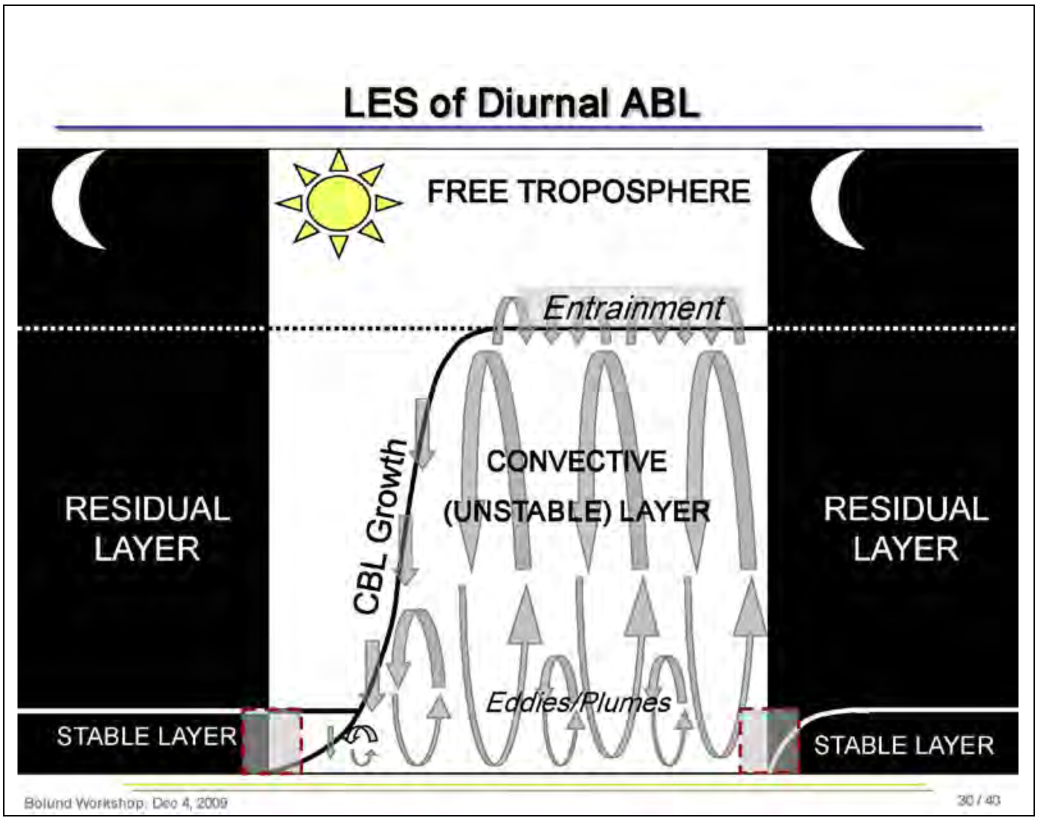
Unstable ABL (Schmidt & Schumann, 1989; Nieuwstadt et al., 1991)

- Suited for LES: Large-scale structures e.g. plumes, thermals
- Energy spectra: Over-dissipative SGS models

Stable ABL (Kosovic & Curry, 2000; Beare et al., 2006)

- Small-scale structures: Burden on SGS model
- Poor SGS models: Numerical instabilities
- Poor representation of energy spectra
- High resolution required with non-dynamic SGS models


SGS model performance: Energy spectra
Unstable (0.2 Km/s) and Stable (-0.02 Km/s) simulations:
Lagrangian Dynamic Scale-invariant and Scale-dependent models
LASI
LASD
Unstable
Stable
Under-dissipative
kz
29 / 40


LES of Diurnal ABL
FREE TROPOSPHERE
Entrainment
CONVECTIVE
(UNSTABLE) LAYER
CBL Growth
RESIDUAL
LAYER
RESIDUAL
LAYER
Eddies/Plumes
STABLE LAYER
STABLE LAYER
Bolund Workshop, Dec 4, 2009
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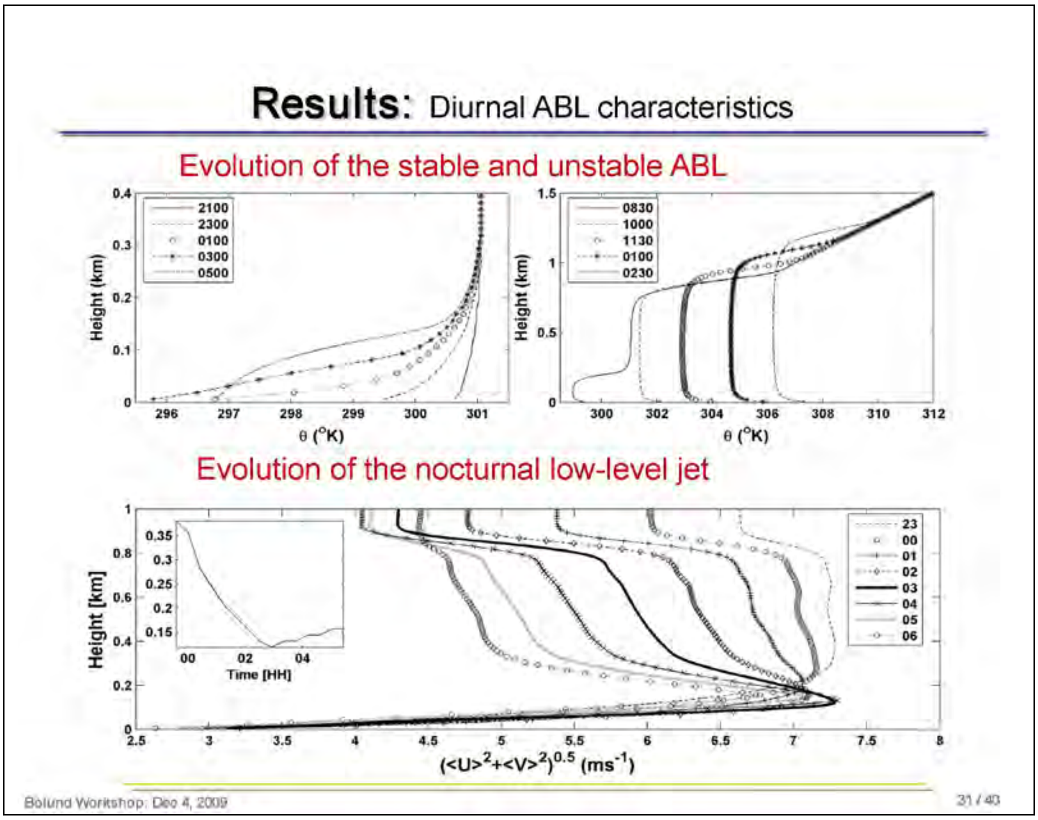

Results: Diurnal ABL characteristics
Evolution of the stable and unstable ABL
Height (km)
θ (°K)
2100
2300
0100
0300
0500
0830
1000
1130
0100
0230
Evolution of the nocturnal low-level jet
Height [km]
Time [HH]
$(\langle U\rangle^2+\langle V\rangle^2)^{0.5}$ (ms^{-1})
23
00
01
02
03
04
05
06
Bolund Workshop: Dec 4, 2009
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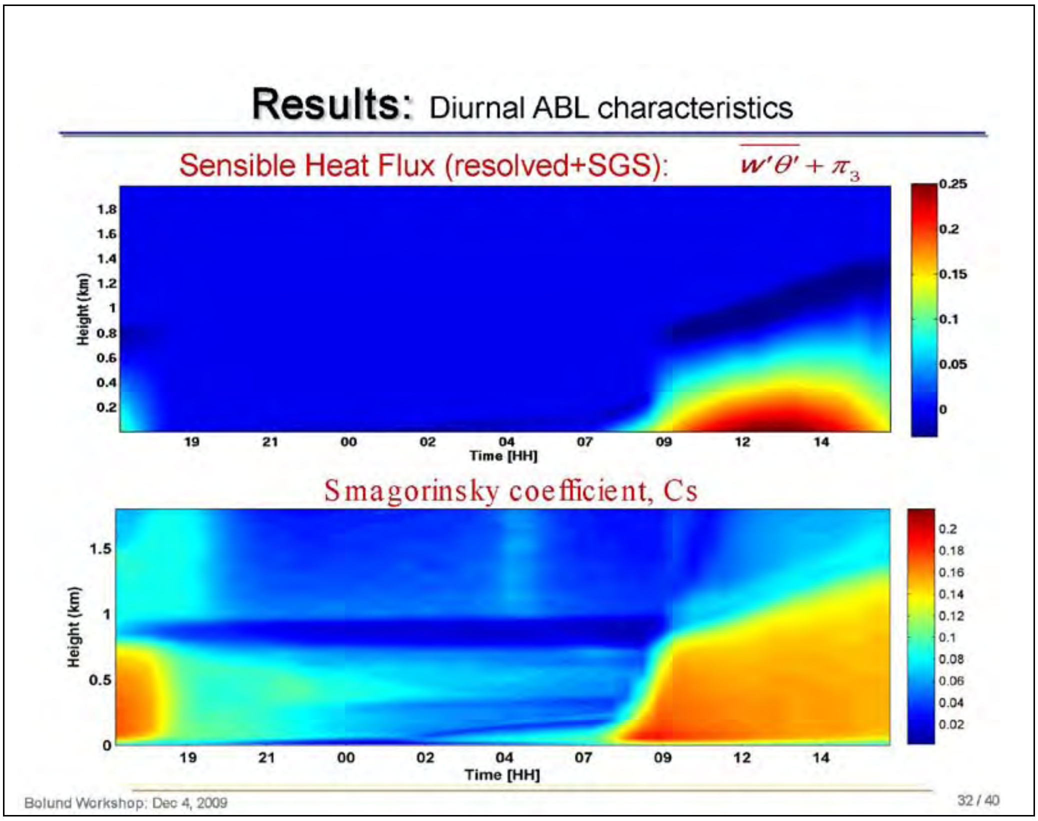

Results: Diurnal ABL characteristics
Sensible Heat Flux (resolved+SGS): $\overline{w'\theta'} + \pi_3$
Height (km)
Time [HH]
Smagorinsky coefficient, Cs
Height (km)
Time [HH]
Bolund Workshop: Dec 4, 2009
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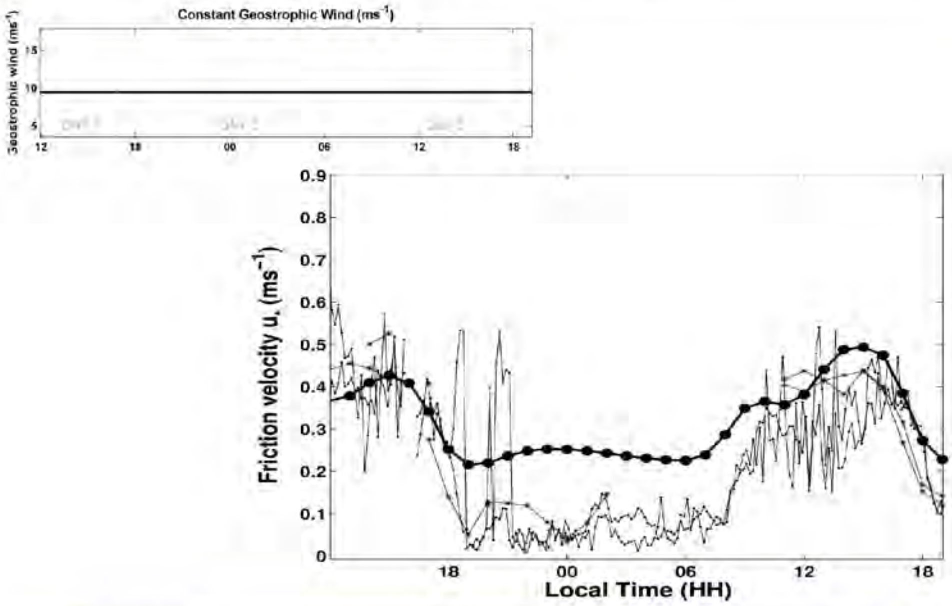
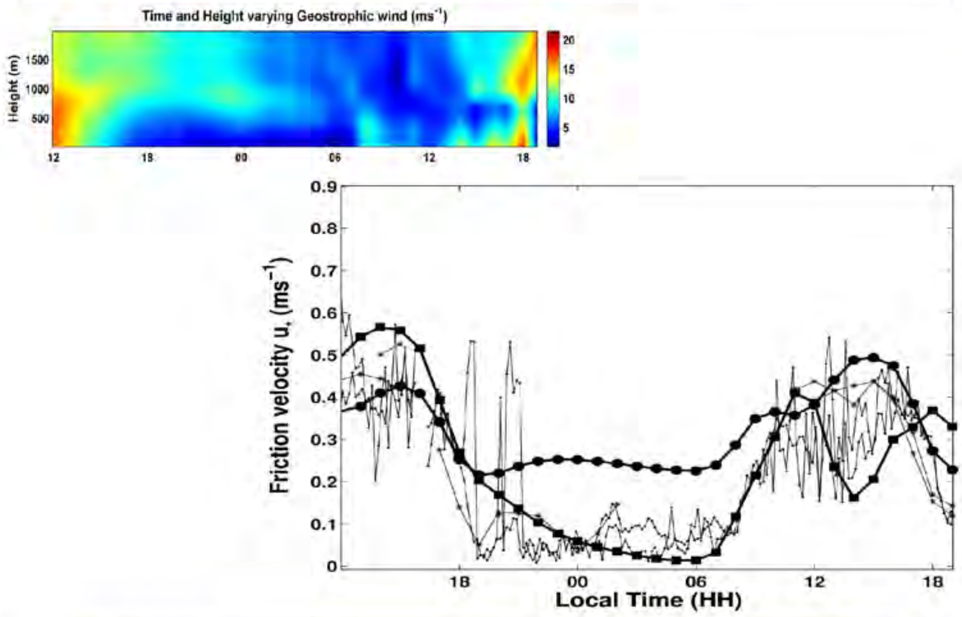
LES: Impact of Pressure forcing/BC



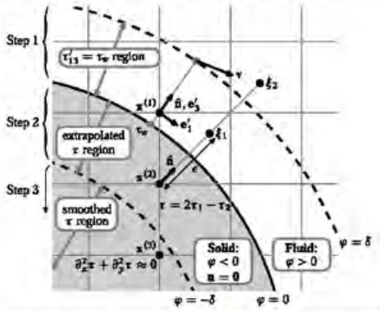
LES: Impact of Pressure forcing/BC

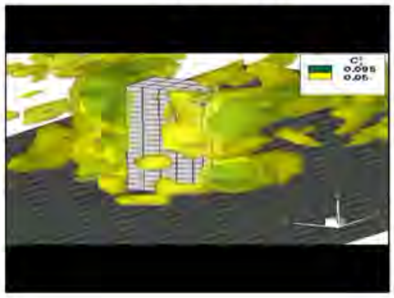


LES: Representation of structures and topography

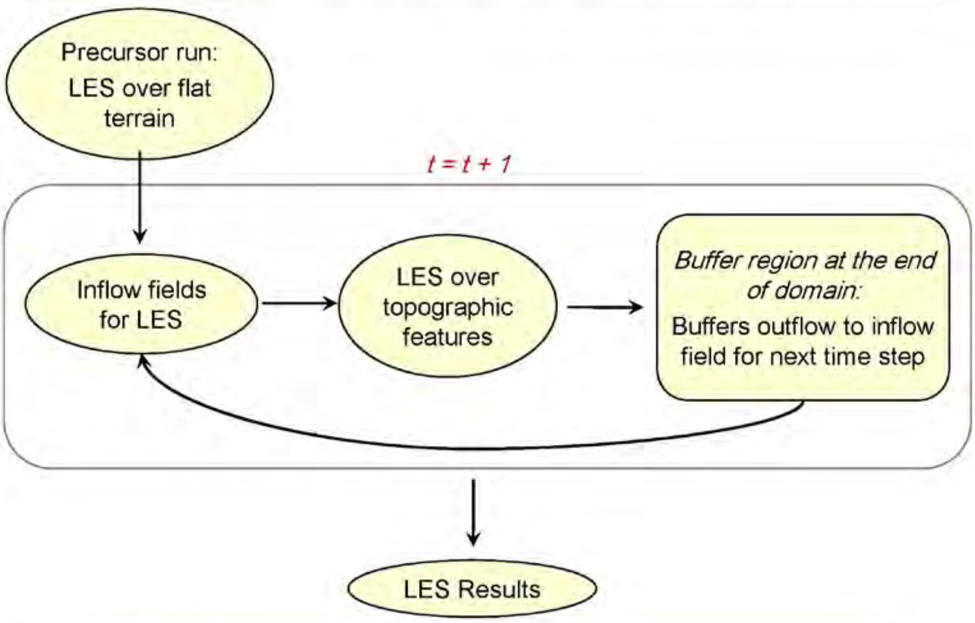
Methodology:

1. Describe surface using the level set method & Fluid-structure interaction represented through immersed boundary method
2. Define a band just outside the surface
3. Pick a point define the surface normal
4. Define a tangential velocity and apply a log law to obtain the sheer stress
5. Extrapolate the stress field into the body
6. Smooth the stress profile inside the body using iterative over-relaxation of the Laplace equation in stress, τ

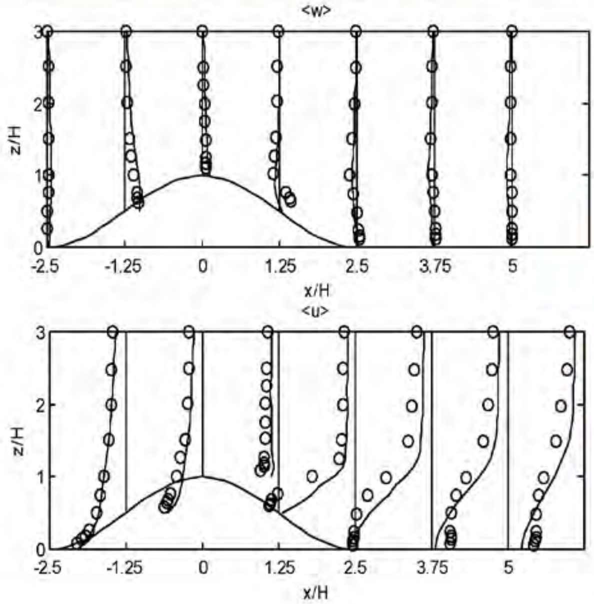


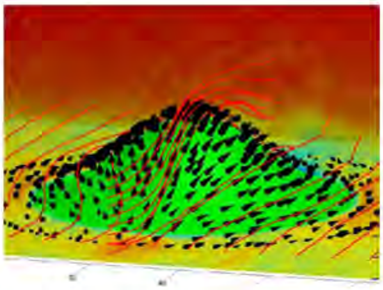


LES: Simulation setup for flow over terrain



LES study: Flow over a Gaussian Hill

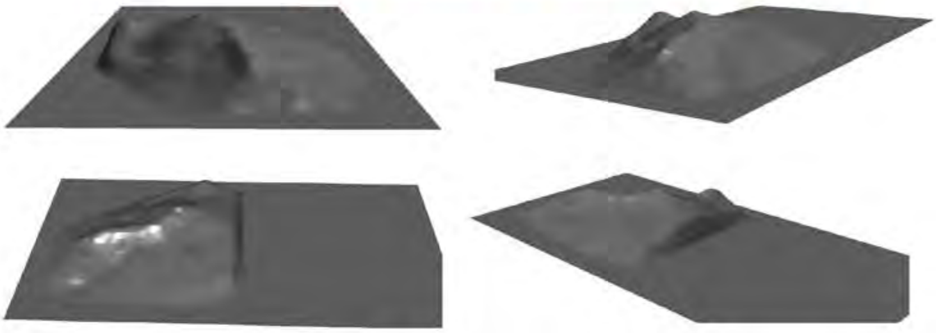


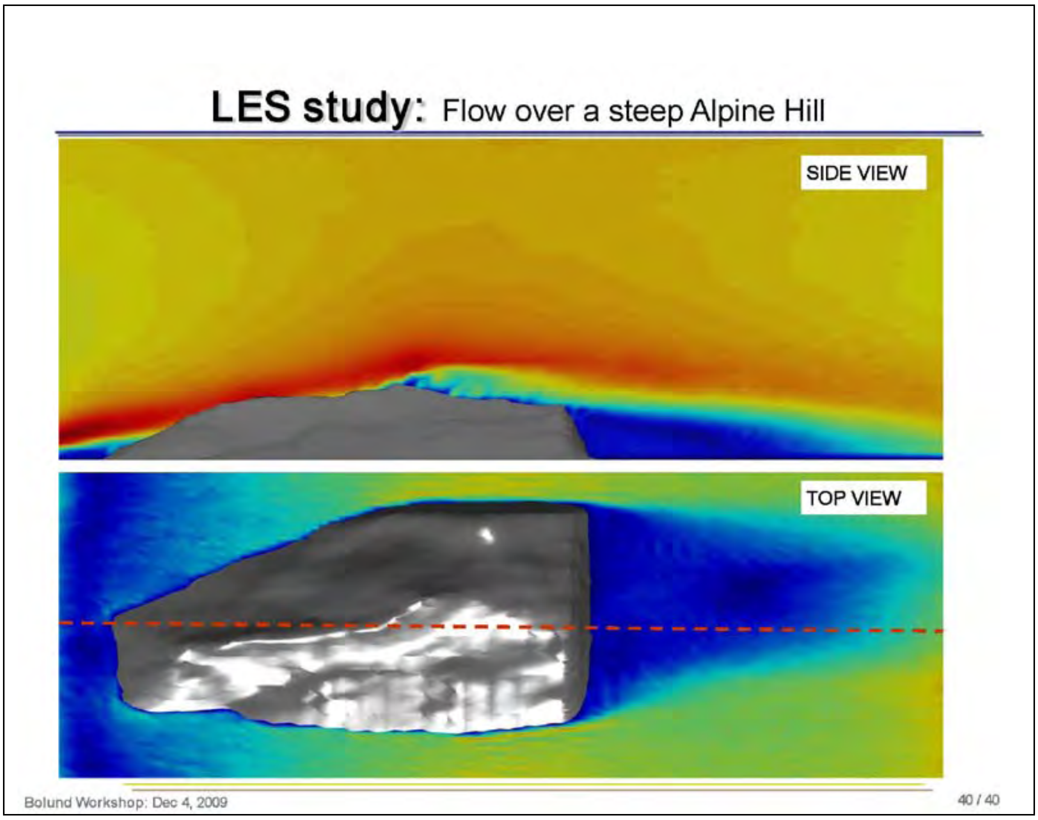


Data from Iwamura et al, 1991

LES study: Flow over a steep real-world Hill

- Gaudergrat ridge, Switzerland
- Dimensions: 1.5kmx1kmx250m
- Slopes of about 45 degrees
- Results to be compared with extensive observations, RANS and mesoscale models




LES study: Flow over a steep Alpine Hill
SIDE VIEW
TOP VIEW
Bolund Workshop: Dec 4, 2009
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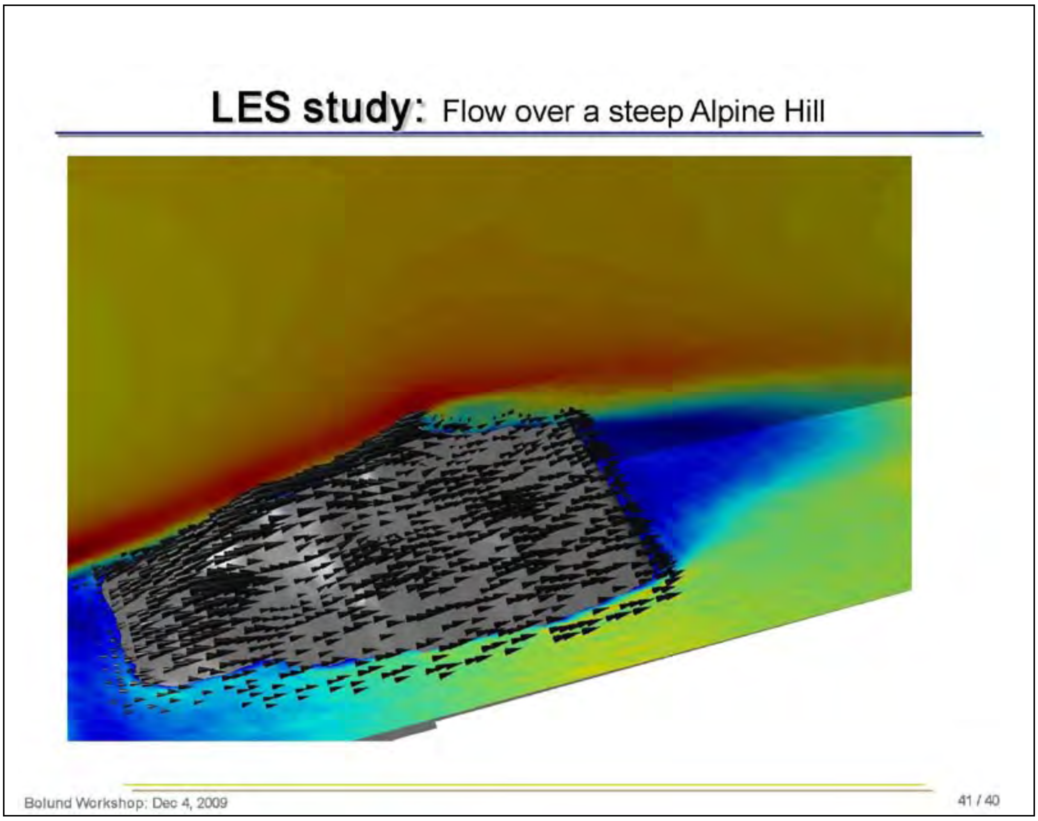
LES study: Flow over a steep Alpine Hill
Bolund Workshop: Dec 4, 2009
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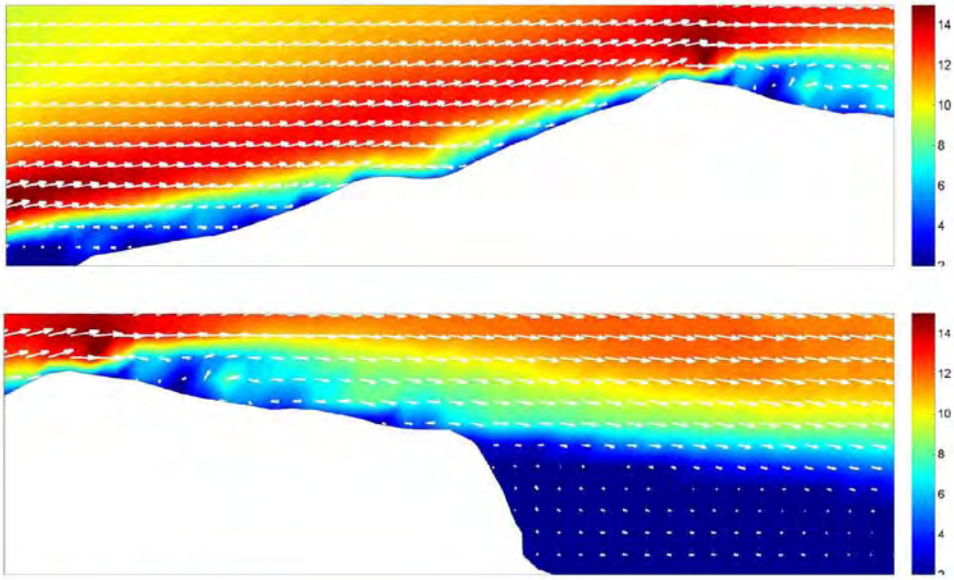
LES study: Flow over a steep Alpine Hill



Bolund Workshop: Dec 4, 2009 42 / 40

LES study: Flow over a steep Alpine Hill

- Cross ridge flows have been observed even when the mean wind direction is along the ridge*
- Also seen in mesoscale simulation of Gaudergradt ridge (Courtesy: Rebecca Mott)
- In LES results, we observe cross-ridge flows with ~20% strength of the predominant flow along the ridge.

Cross ridge flow

*Lewis et al. (2008), QJRMS

Bolund Workshop: Dec 4, 2009 43 / 40


LES study: Flow over a steep real-world Hill
Bolund Workshop: Dec 4, 2009
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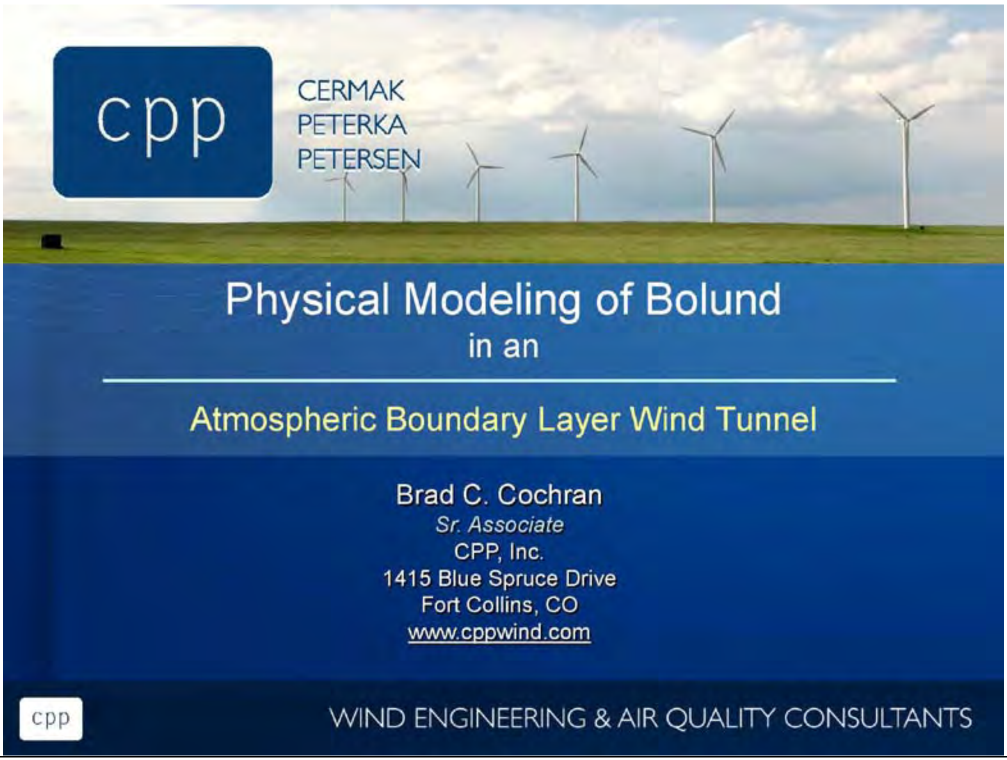
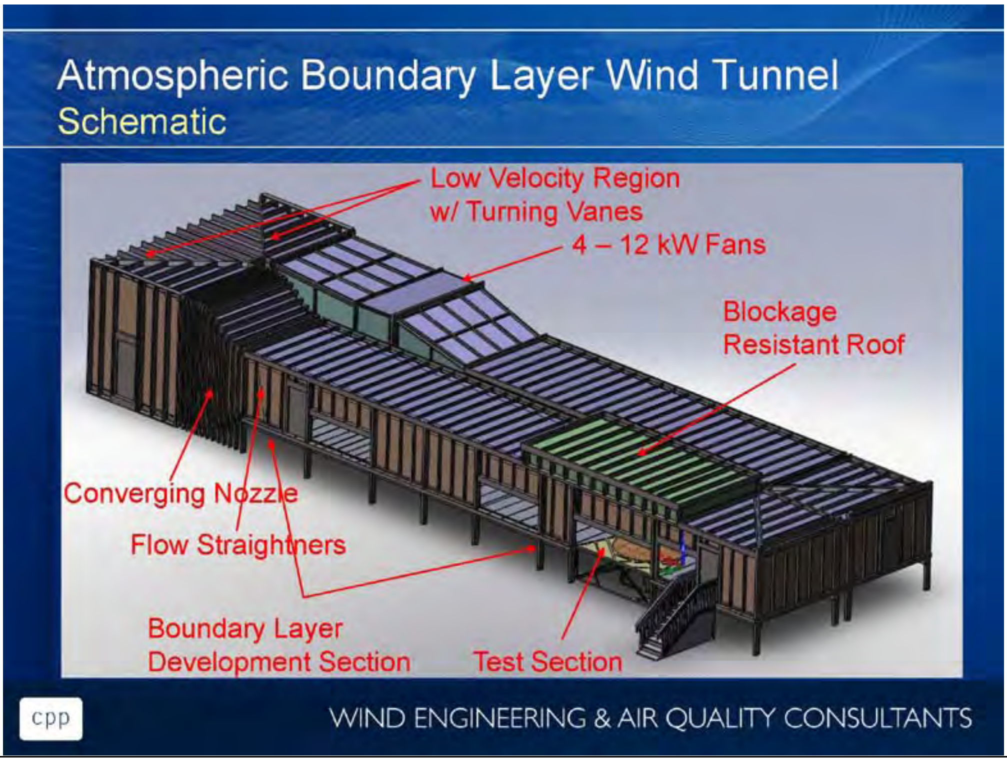
“Physical Modeling of Bolund” - by Brad C. Cochran





Typical Applications
Wind Induced Building Loads

Superdome and New Orleans Arena

John Hancock Building - Boston →

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Typical Applications
Pedestrian Level Wind Environment

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Typical Applications
Plume Dispersion
WIND
cpp
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Typical Applications
Airflow in Complex Terrain Environments
Speed-up
(Upwind)
(Downwind)
2-D Ridge or 3-D Axisymmetrical Hill
cpp
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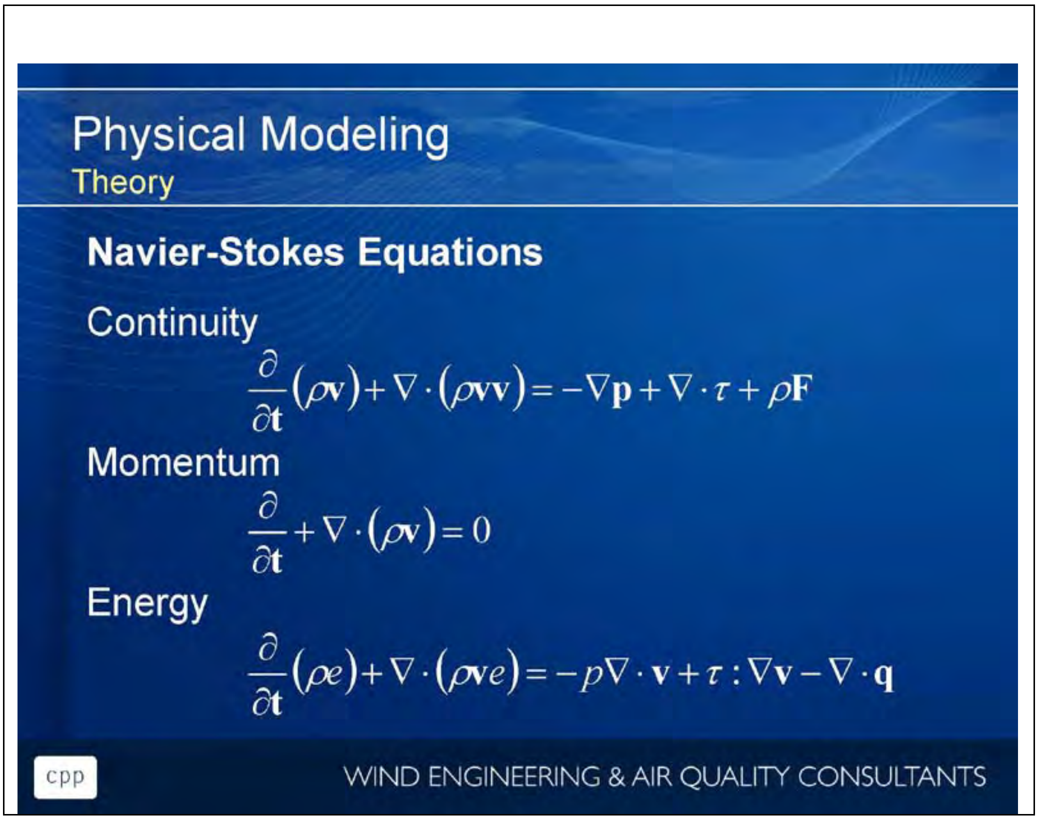
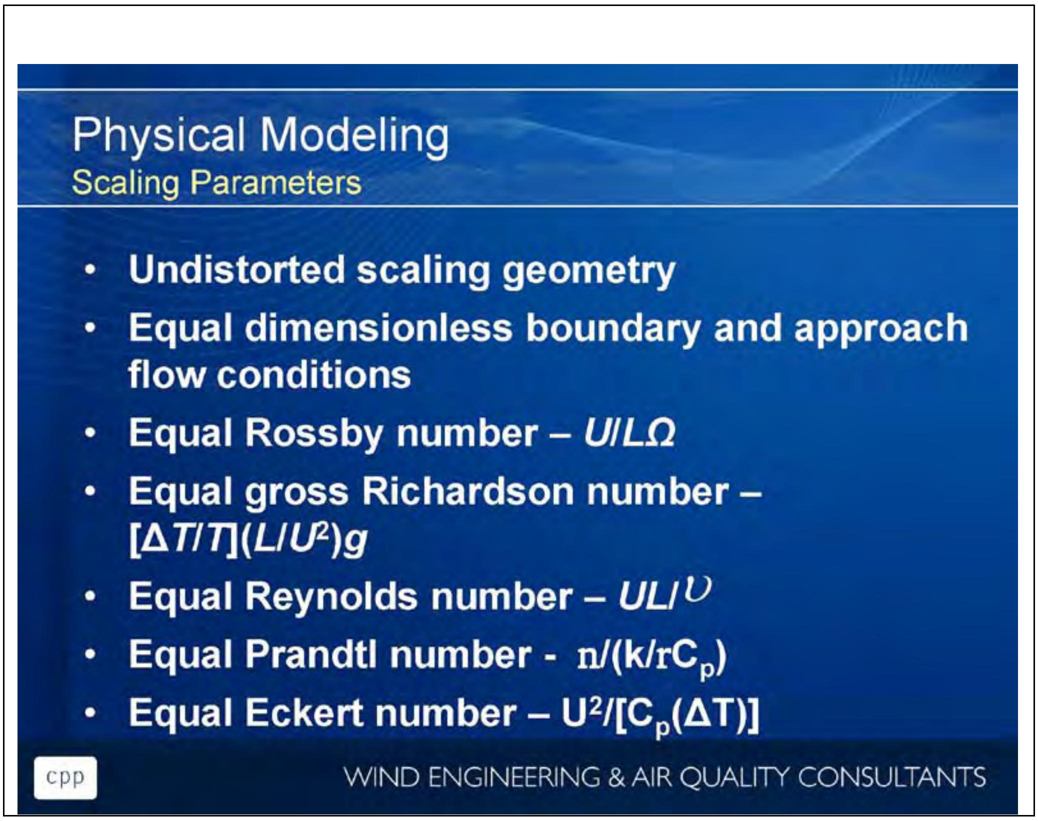
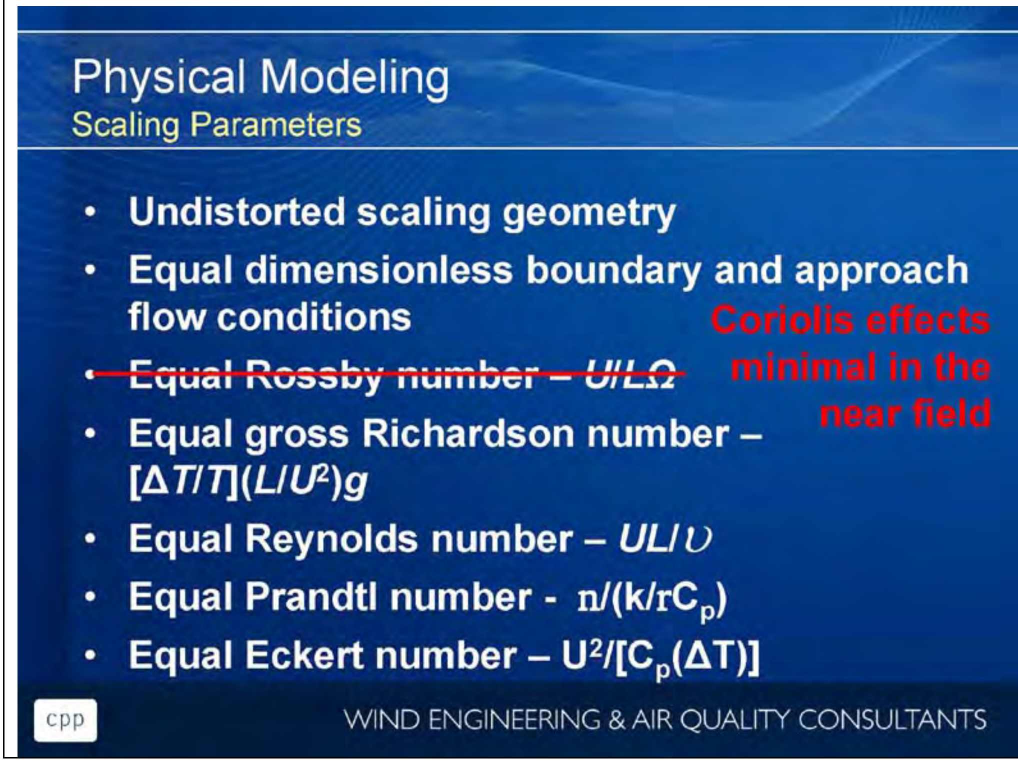
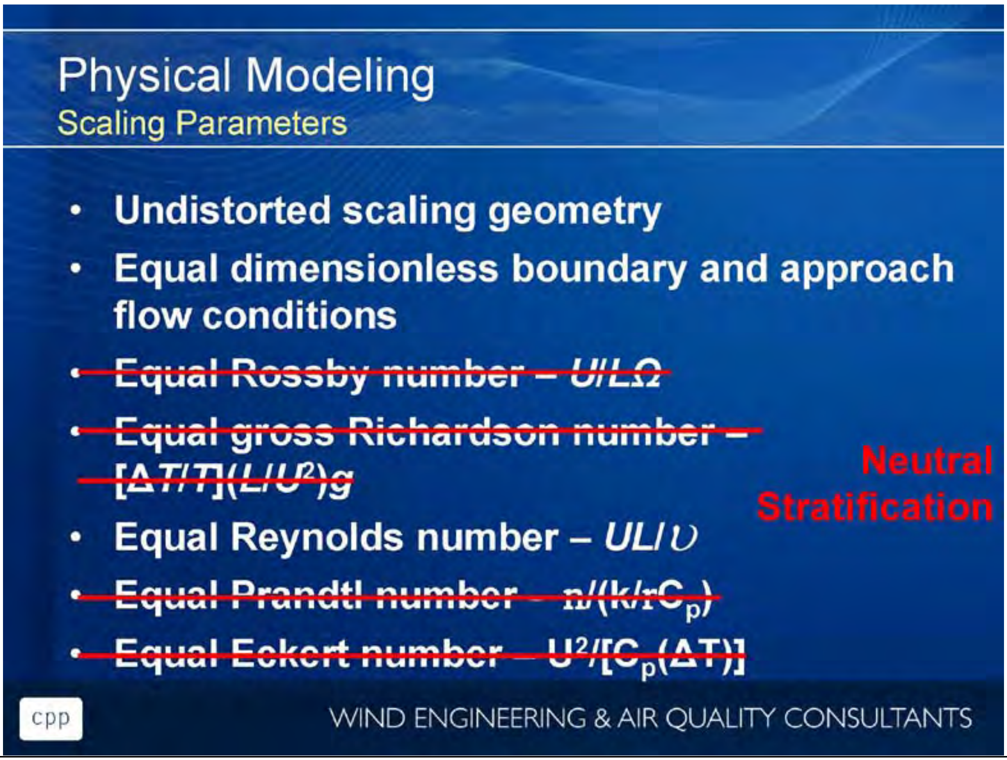

Physical Modeling
Theory
Navier-Stokes Equations
Continuity
$$\frac{\partial}{\partial \mathbf{t}}(\rho\mathbf{v})+\nabla\cdot(\rho\mathbf{v}\mathbf{v})=-\nabla\mathbf{p}+\nabla\cdot\tau+\rho\mathbf{F}$$
Momentum
$$\frac{\partial}{\partial \mathbf{t}}+\nabla\cdot(\rho\mathbf{v})=0$$
Energy
$$\frac{\partial}{\partial \mathbf{t}}(\rho e)+\nabla\cdot(\rho\mathbf{v}e)=-p\nabla\cdot\mathbf{v}+\tau:\nabla\mathbf{v}-\nabla\cdot\mathbf{q}$$
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Physical Modeling
Scaling Parameters
• Undistorted scaling geometry
• Equal dimensionless boundary and approach flow conditions
• Equal Rossby number – $U/L\Omega$
• Equal gross Richardson number – $[\Delta T/T](L/U^2)g$
• Equal Reynolds number – UL/υ
• Equal Prandtl number - $n/(k/rC_p)$
• Equal Eckert number – $U^2/[C_p(\Delta T)]$
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Physical Modeling
Scaling Parameters
• Undistorted scaling geometry
• Equal dimensionless boundary and approach flow conditions
~~• Equal Rossby number – U/LΩ~~
• Equal gross Richardson number – [ΔT/T](L/U²)g
• Equal Reynolds number – UL/υ
• Equal Prandtl number - n/(k/rC$_p$)
• Equal Eckert number – U²/[C$_p$(ΔT)]
Coriolis effects minimal in the near field
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Physical Modeling
Scaling Parameters
• Undistorted scaling geometry
• Equal dimensionless boundary and approach flow conditions
~~• Equal Rossby number – U/LΩ~~
~~• Equal gross Richardson number – [ΔT/T](L/U²)g~~
• Equal Reynolds number – UL/υ
~~• Equal Prandtl number - n/(k/rC$_p$)~~
~~• Equal Eckert number – U²/[C$_p$(ΔT)]~~
Neutral Stratification
cpp
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Physical Modeling

Scaling Parameters

$$\left(\frac{UL}{\upsilon}\right)_{\text{model}} = \left(\frac{UL}{\upsilon}\right)_{\text{fullscale}}$$

$$(L)_{\text{model}} = (L)_{\text{fullscale}} / 100$$

$$(\upsilon)_{\text{model}} = (\upsilon)_{\text{fullscale}}$$

$$\downarrow$$

$$\cancel{(U)_{model} = (U)_{fullscale} \times 100 = 1{,}000\, m/s}$$

NOT POSSIBLE!

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Physical Modeling

Reynolds Number Independence

- Ensure a fully turbulent wake flow

  Terrain or Building Reynolds Number greater than 11,000 ($R_{e_T} = UH_T/\upsilon$)

  $U = 10$ m/s

  $H_T = 0.25$ m

  $\upsilon = 1.15\text{x}10^{-5}$ m²/s

  $R_{e_T} = 217{,}391$

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History
Timeline

Abe (1929) studies air flow over a scale model of Mt. Fuji

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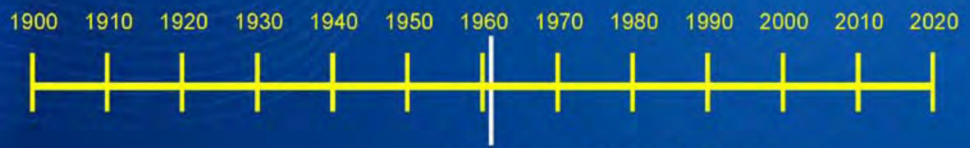
History
Timeline



Golden (1961) Defines minimum acceptable Reynolds number to achieve Reynolds number independence

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History
Timeline
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
Cermak and Davenport (1964) measured wind loads on a scale model of the World Trade Centers in New York
cpp
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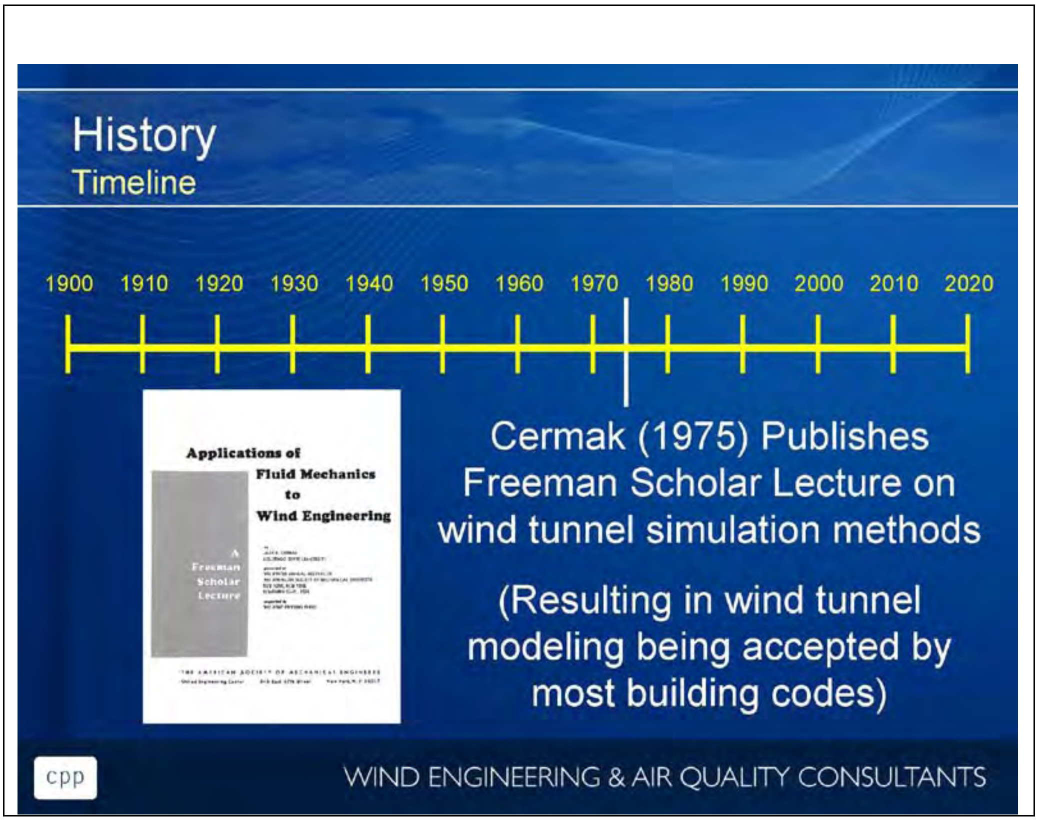
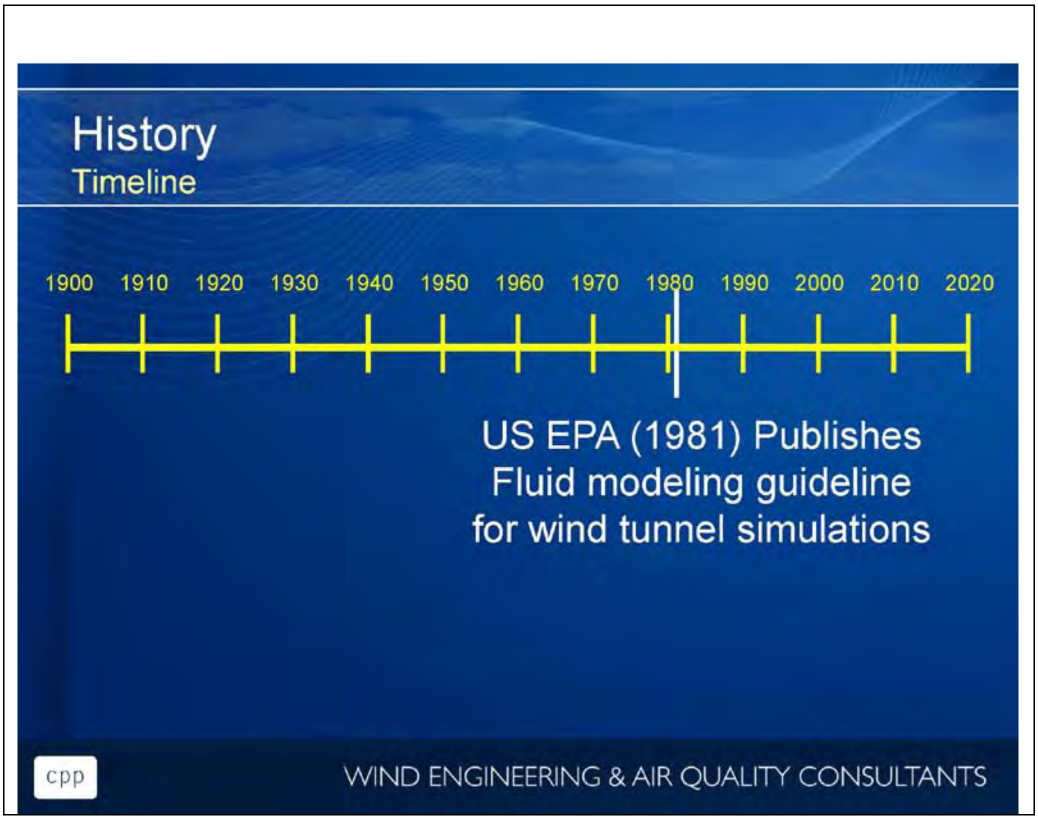
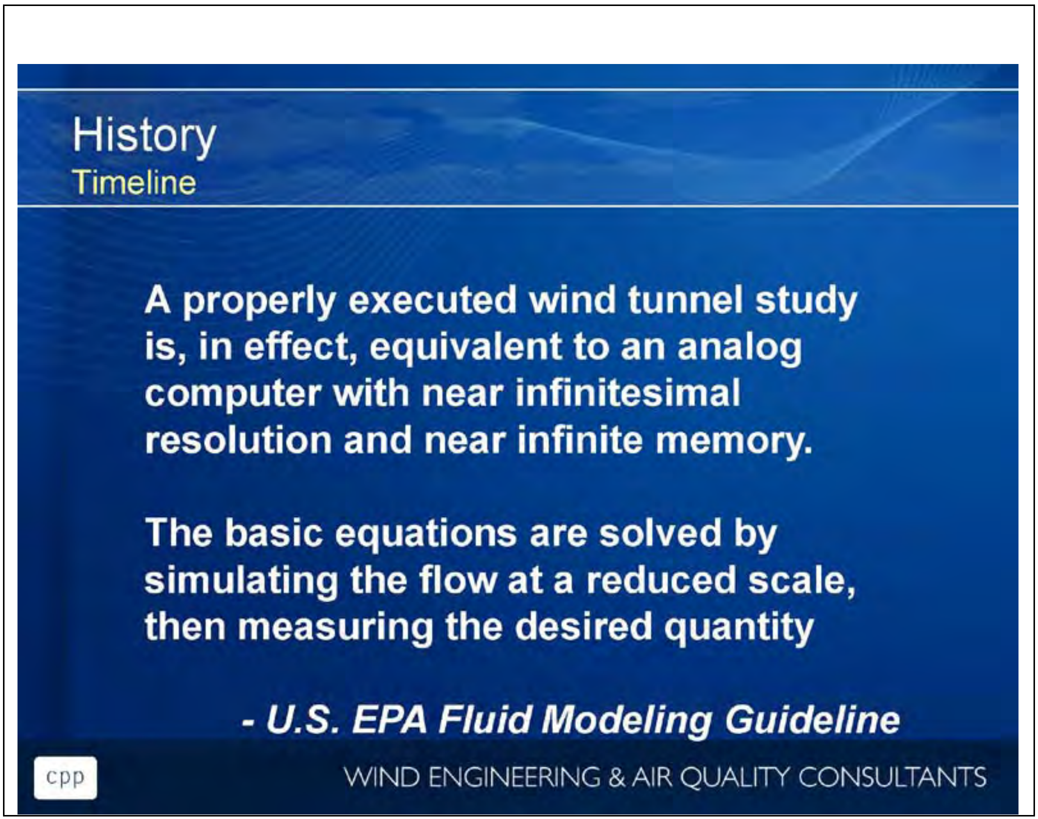

History
Timeline
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
Applications of
Fluid Mechanics
to
Wind Engineering
A
Freeman
Scholar
Lecture
Cermak (1975) Publishes Freeman Scholar Lecture on wind tunnel simulation methods
(Resulting in wind tunnel modeling being accepted by most building codes)
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


History
Timeline
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
US EPA (1981) Publishes
Fluid modeling guideline
for wind tunnel simulations
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


History
Timeline
A properly executed wind tunnel study is, in effect, equivalent to an analog computer with near infinitesimal resolution and near infinite memory.
The basic equations are solved by simulating the flow at a reduced scale, then measuring the desired quantity
- U.S. EPA Fluid Modeling Guideline
cpp
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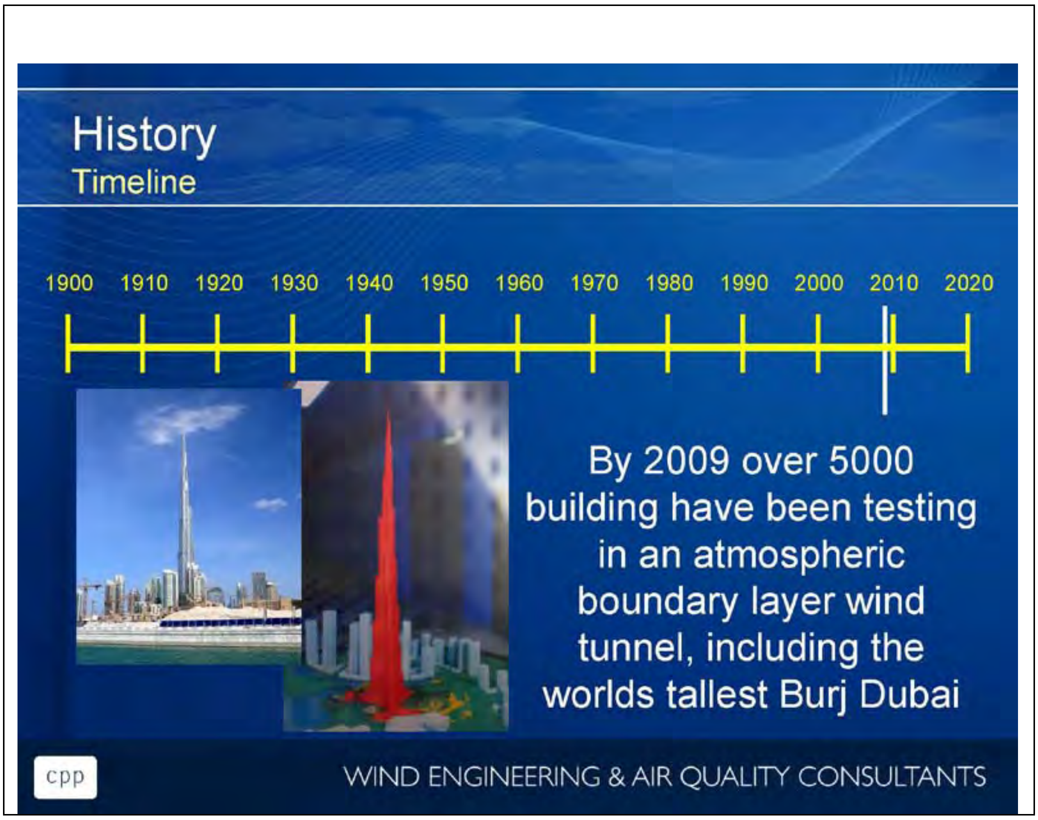
History
Timeline
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
By 2009 over 5000 building have been testing in an atmospheric boundary layer wind tunnel, including the worlds tallest Burj Dubai
cpp
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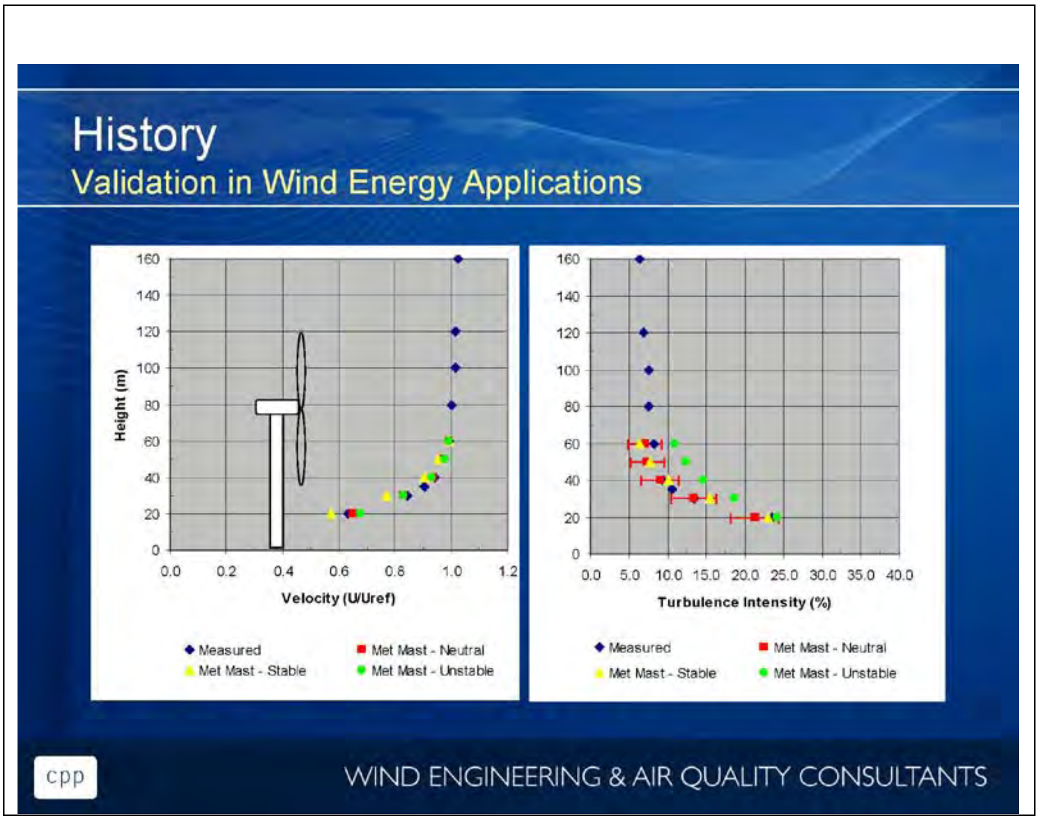
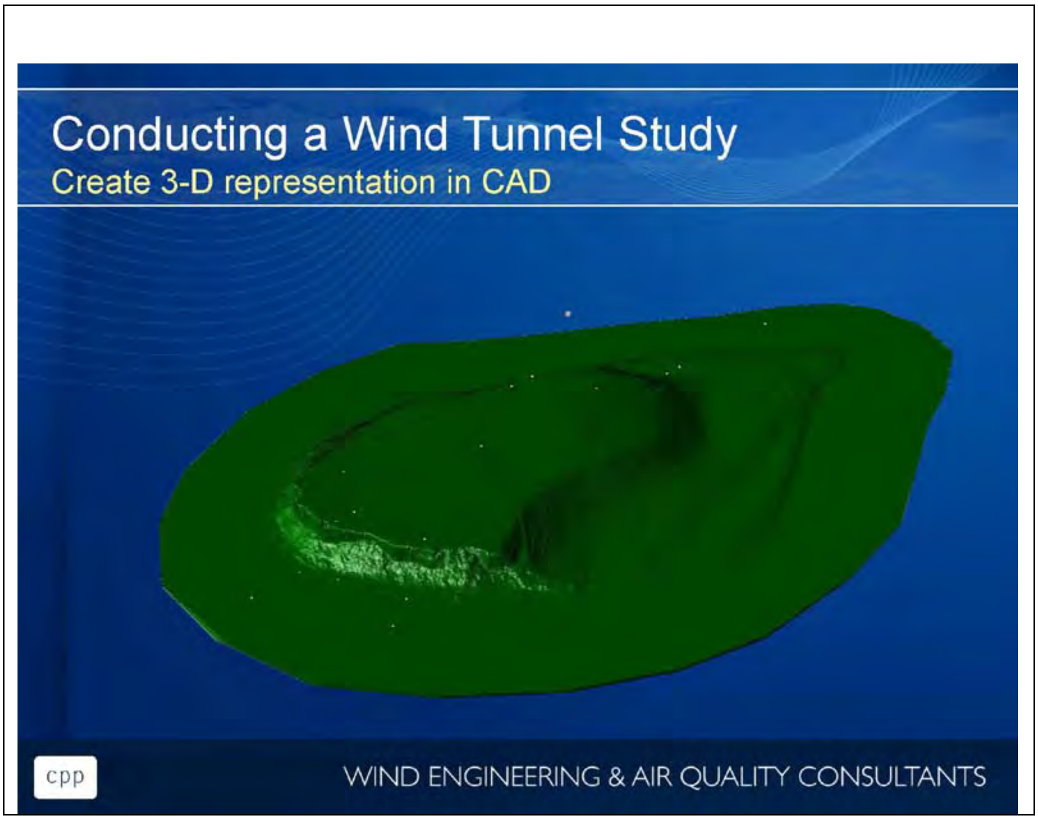
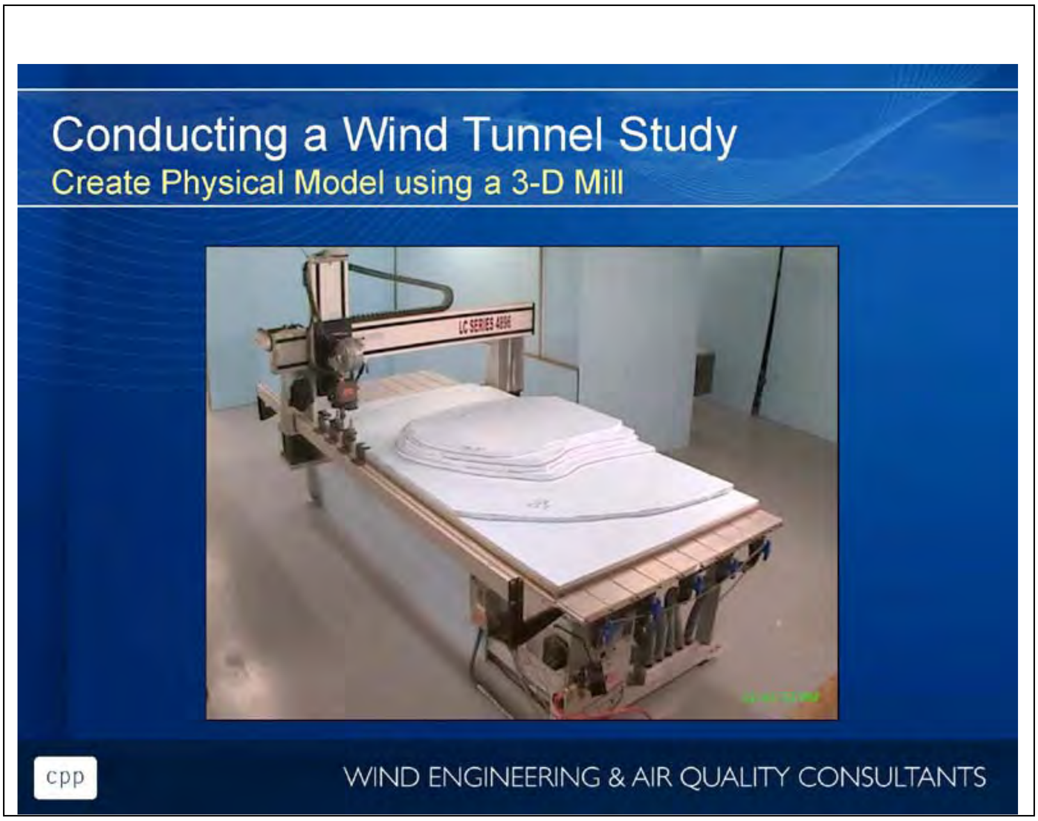
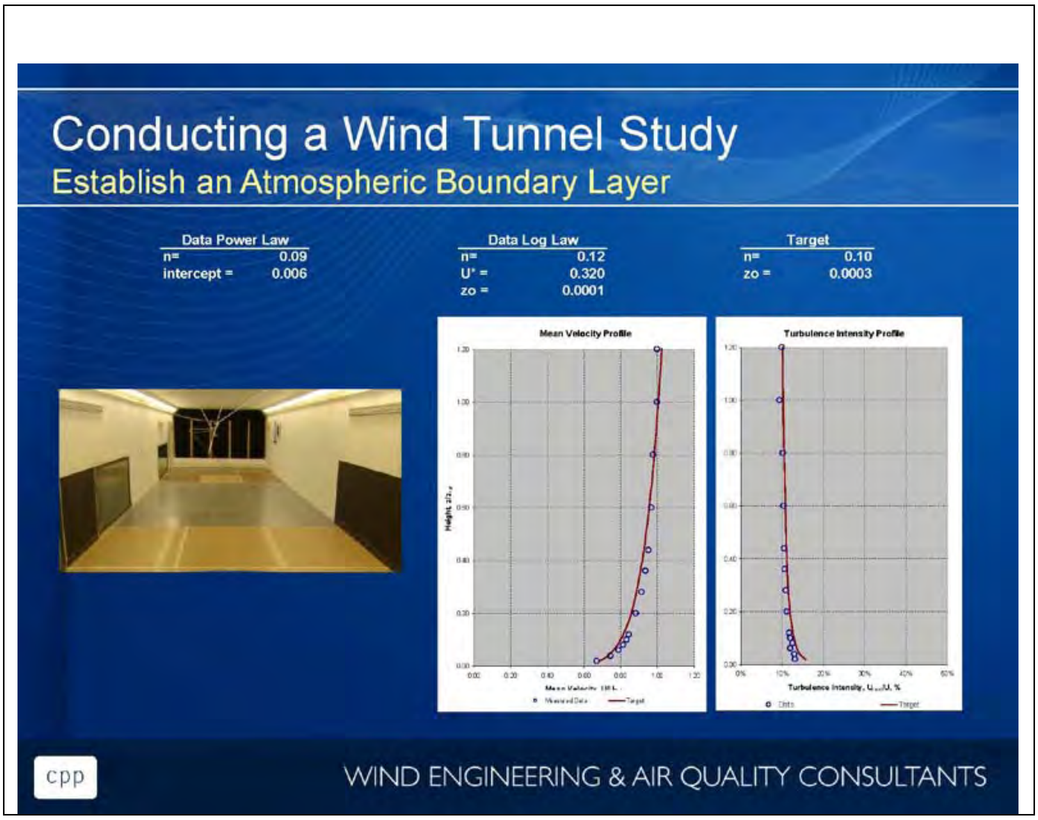
History
Validation in Wind Energy Applications
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


History
Validation in Wind Energy Applications
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


History
Validation in Wind Energy Applications
Height (m)
Velocity (U/Uref)
Turbulence Intensity (%)
Measured
Met Mast - Neutral
Met Mast - Stable
Met Mast - Unstable
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Conducting a Wind Tunnel Study
Create 3-D representation in CAD
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Conducting a Wind Tunnel Study
Create Physical Model using a 3-D Mill
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Conducting a Wind Tunnel Study
Establish an Atmospheric Boundary Layer
Data Power Law
n= 0.09
intercept = 0.006
Data Log Law
n= 0.12
U* = 0.320
zo = 0.0001
Target
n= 0.10
zo = 0.0003
Mean Velocity Profile
Turbulence Intensity Profile
cpp
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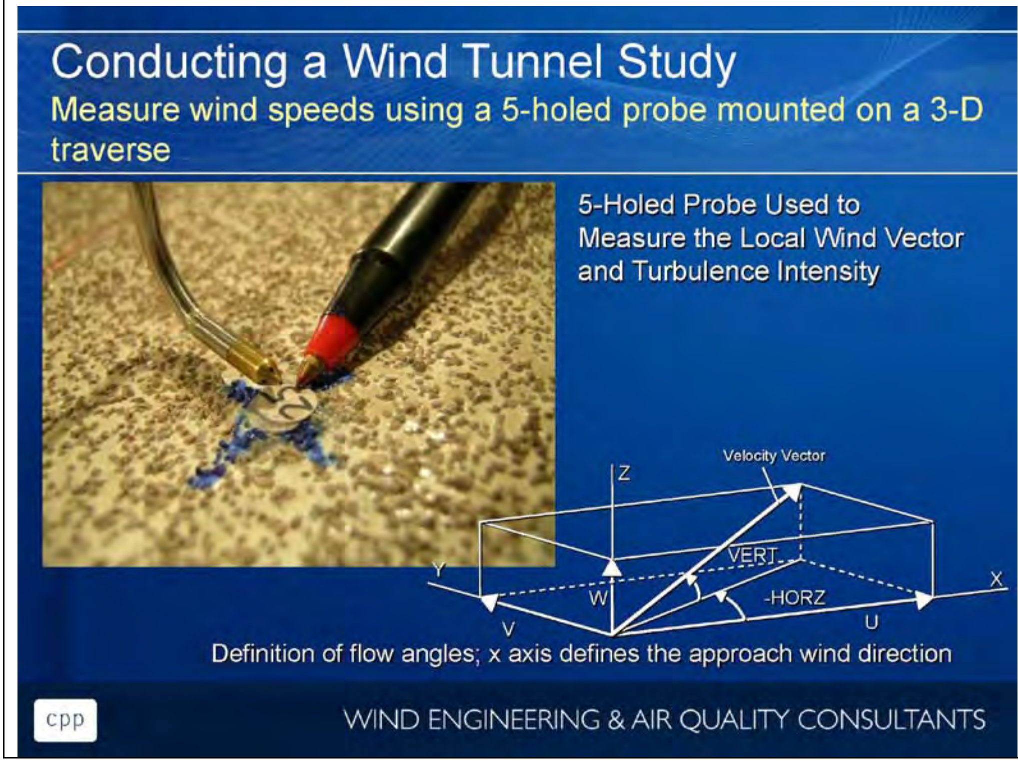
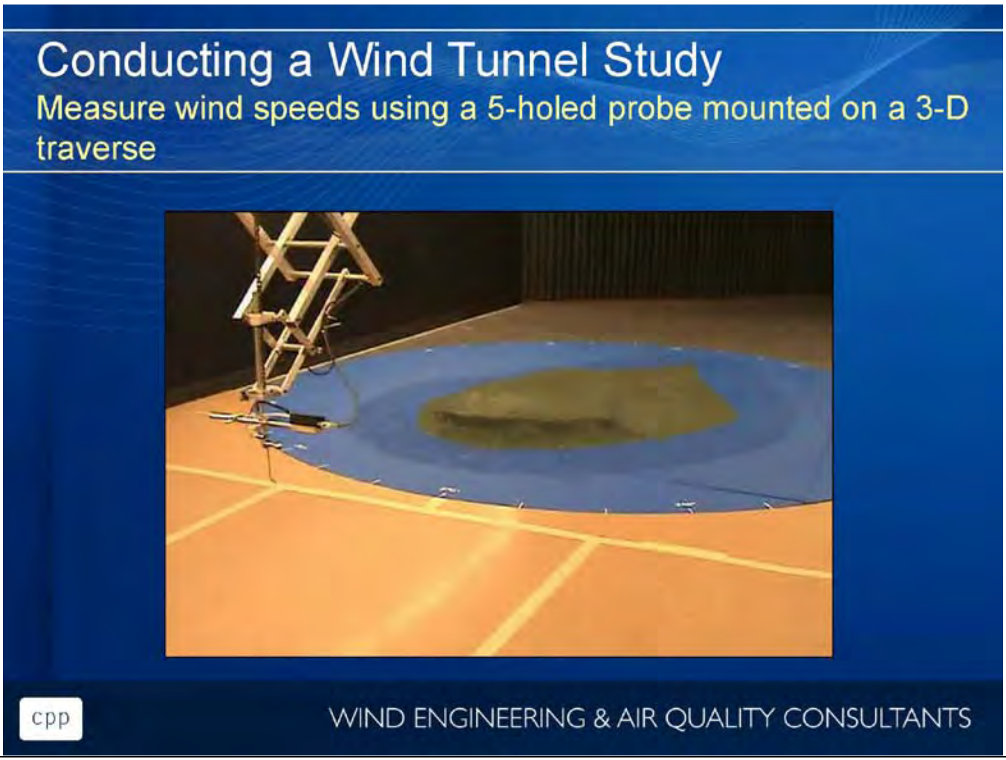
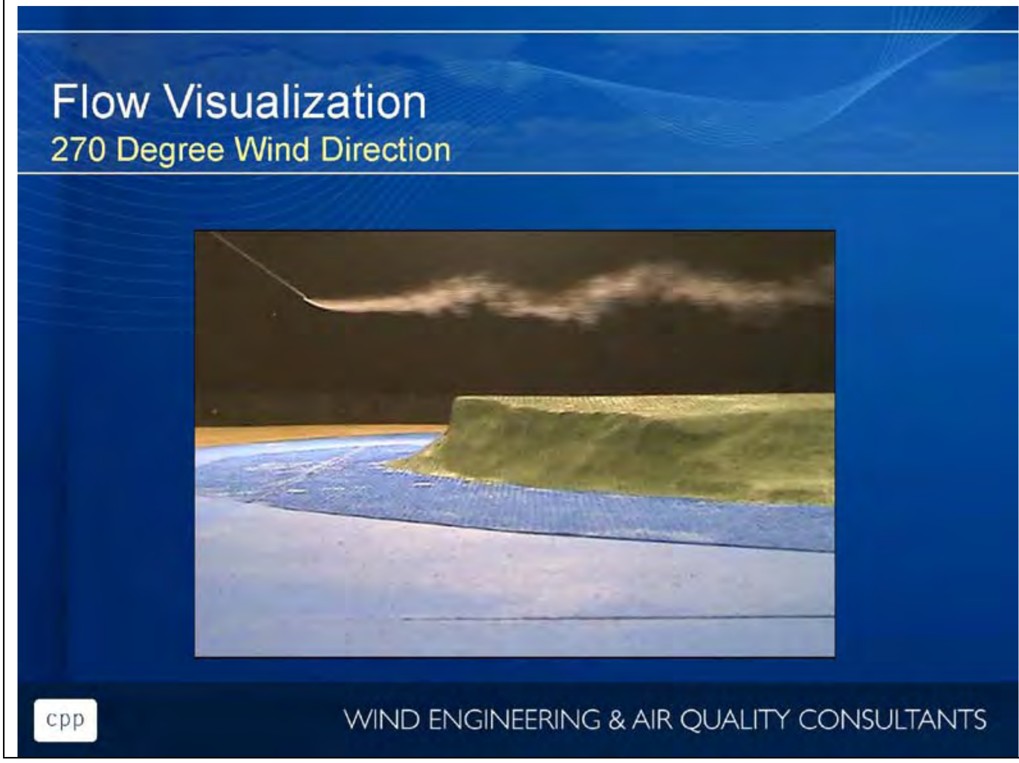
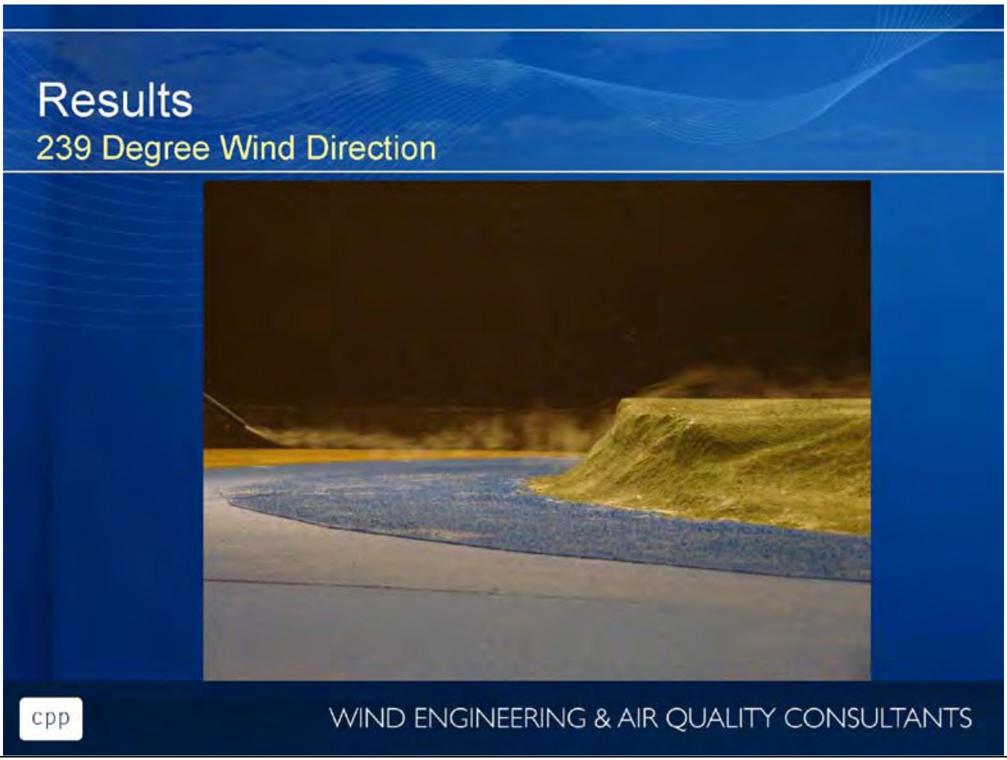
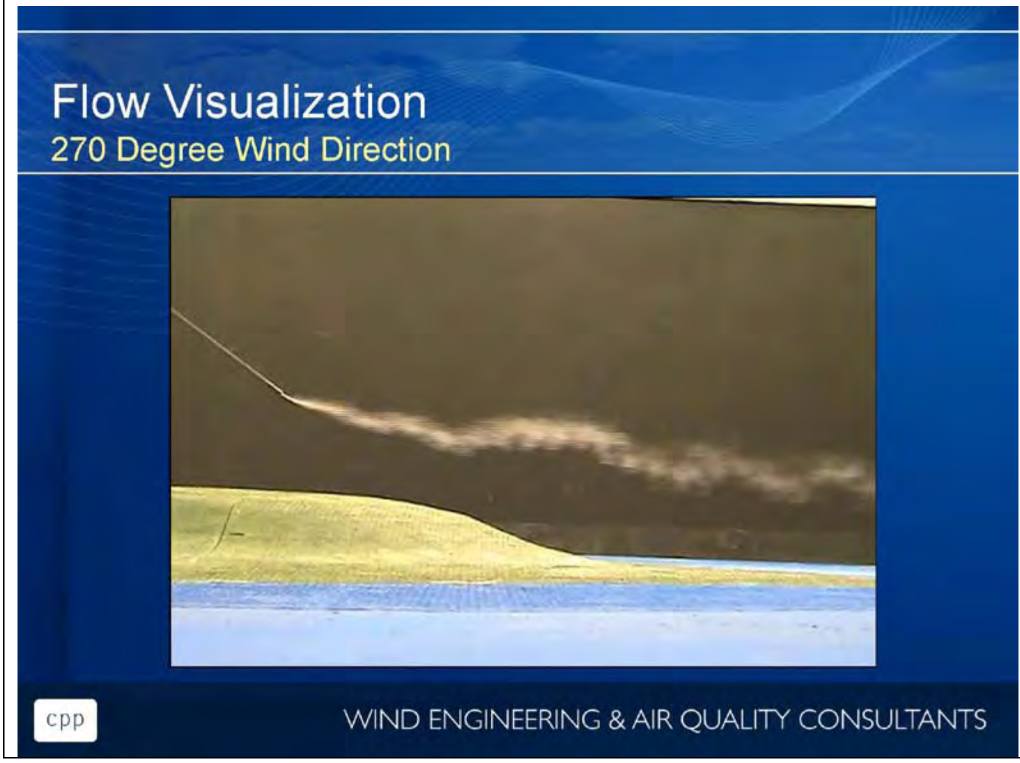
Conducting a Wind Tunnel Study
Install Model in the Wind Tunnel
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS

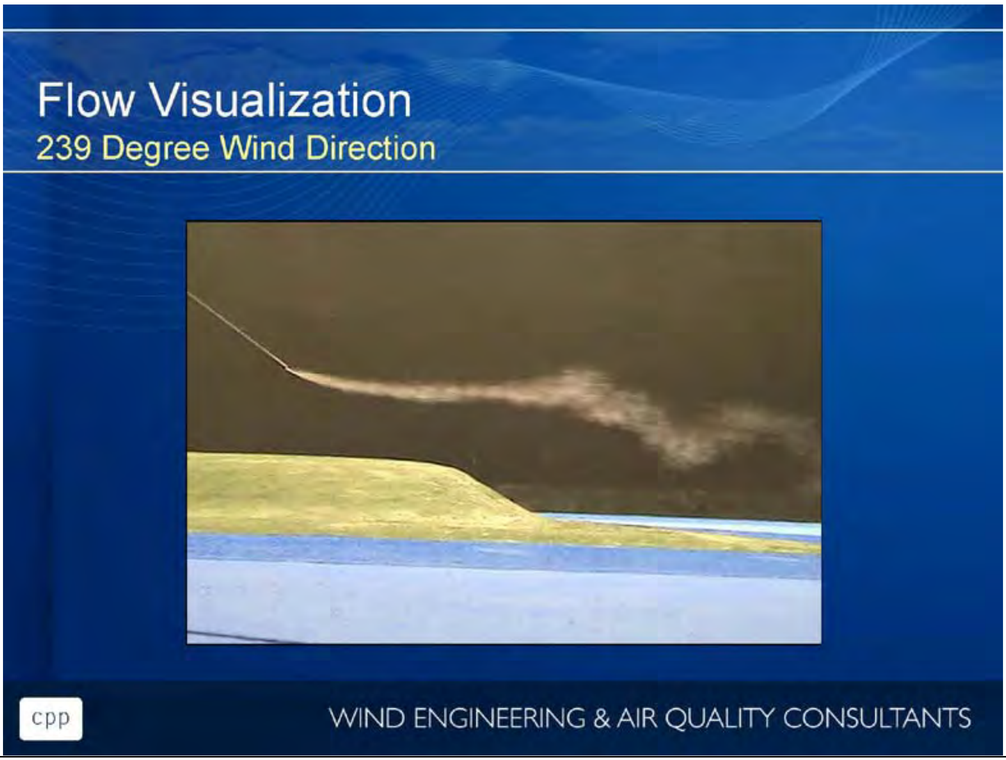

Conducting a Wind Tunnel Study
Measure wind speeds using a 5-holed probe mounted on a 3-D traverse
5-Holed Probe Used to Measure the Local Wind Vector and Turbulence Intensity
Velocity Vector
Z
VERT
Y
X
W
-HORZ
V
U
Definition of flow angles; x axis defines the approach wind direction
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS

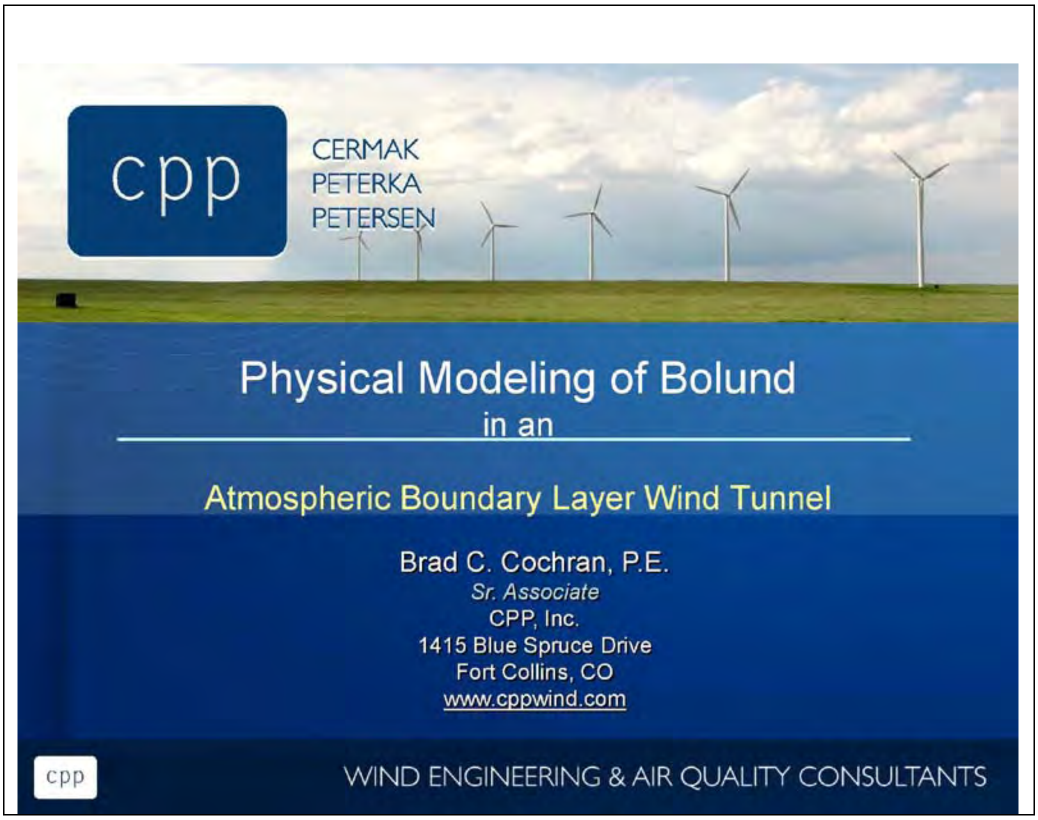

Conducting a Wind Tunnel Study
Measure wind speeds using a 5-holed probe mounted on a 3-D traverse
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Flow Visualization
270 Degree Wind Direction
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Results
239 Degree Wind Direction
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


Flow Visualization
270 Degree Wind Direction
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS

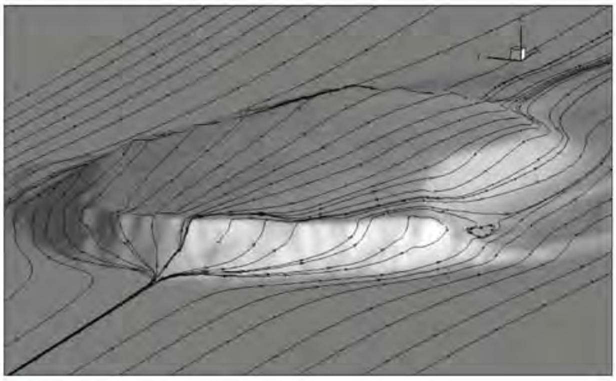

Flow Visualization
239 Degree Wind Direction
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS


cpp
CERMAK
PETERKA
PETERSEN
Physical Modeling of Bolund
in an
Atmospheric Boundary Layer Wind Tunnel
Brad C. Cochran, P.E.
Sr. Associate
CPP, Inc.
1415 Blue Spruce Drive
Fort Collins, CO
www.cppwind.com
cpp
WIND ENGINEERING & AIR QUALITY CONSULTANTS

“RANS CFD simulations of flow around Bolund” - by Niels Sørensen

RANS CFD simulations of flow around Bolund

Niels N. Sørensen and Andreas Bechmann



Risø DTU
National Laboratory for Sustainable Energy

Outline

- CFD solver for terrain flow
  - Turbulence modeling
  - Boundary conditions
  - Roughness
- Computational domain and surface discretization
- Brief overview of present simulations, number of points and computing time
- Verification of the simulations, Convergence and Grid Convergence.
- Problems when comparing with measurements.
- Terrain resolution.
- A few examples of the results
- Conclusion

2 **Risø DTU, Technical University of Denmark** RANS predictions of Bolund 03/12/2009

Components of a CFD methodology

- Preprocessor
  - Geometry processor (CAD)
  - Grid Generation
  - Specification of Boundary Conditions
  - Roughness treatment
- CFD solver
  - Accurate
  - Efficient solver
  - Versatile
- Postprocessor
  - 3D graphics
  - Extraction of velocities, turbulence etc in predefined points

Components of a CFD solver

The basic idea is to take the partial differential equations describing the fluid flow, transform them into a set of algebraic equations, and solve these using a numerical method on a computer.

Typical components of a CFD code are listed below:

- Mathematical Model
  - Turbulence Modeling
- Coordinate and basis vector systems
- Discretization Method, space and time
- Solution Method
- Computational Grid

Turbulence Modeling

- Direct Numerical Simulation (DNS)
- Filtered Equations
  - Large Eddy Simulation (LES)
- Time Averaged Equations, Reynolds Averaged Navier-Stokes(RANS)
  - Algebraic Models (e.g. Baldwin-Lomax)
  - One Equations Models (e.g. Spalart-Allmaras, Baldwin-Barth)
  - Two Equation Models (e.g. k-ω, k-ε)
  - Reynolds Stress Models
- Hybrid Models
  - Detached Eddy Models

5 Risø DTU, Technical University of Denmark RANS predictions of Bolund 03/12/2009

Boundary conditions (Inlet and outlet conditions)

Inflow boundary conditions for Atmospheric flows:

Log-law profiles for the velocities and turbulent quantities.

$$U(z) = \frac{u_\tau}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad , \quad \mu_t = \rho \kappa u_\tau z \ ,$$

$$\epsilon(z) = \frac{C_\mu^{\frac{3}{4}} k^{\frac{3}{2}}}{\kappa z} \quad , \quad k(z) = \frac{u_\tau^2}{\sqrt{C_\mu}} \ .$$

$$C_{\epsilon 1} = C_{\epsilon 2} - \frac{\kappa}{C_\mu^{\frac{1}{2}} \sigma_\epsilon} \ .$$

Outflow boundary conditions:

Fully developed flow is assumed in the mesh direction normal to the outlet.

6 Risø DTU, Technical University of Denmark RANS predictions of Bolund 03/12/2009

Boundary conditions (Wall)

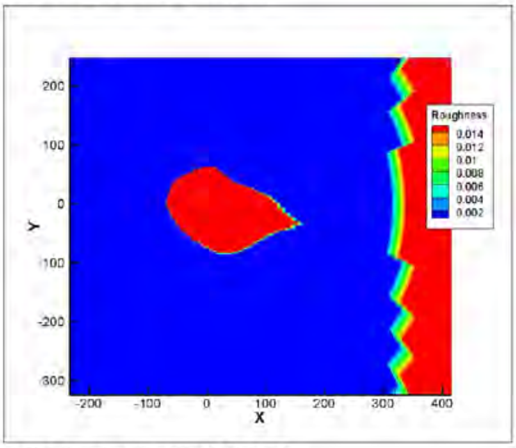
Wall boundary conditions are given by the log-law

- The velocity boundary conditions are implemented through the friction at the wall.
- The implementation assures that flow separation can be handled by evaluating the friction velocity from the turbulent kinetic energy.
- The computational grid is placed on top of the roughness elements, and the actual roughness heights are ignored in connection with the grid generation.
- The TKE boundary condition is an equilibrium between production and dissipation, implemented through a von Neumann condition and specifying the production term from the equilibrium between production and dissipation.
- The epsilon equation is abandoned at the wall, and instead the value of the dissipation is specified according to the equilibrium between production and dissipation.

7 Risø DTU, Technical University of Denmark RANS predictions of Bolund 03/12/2009

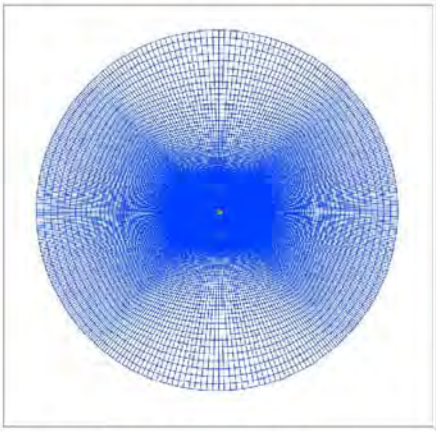
Roughness Maps

- In our case, and maybe in most cases the local roughness is determined based on the (x,y) coordinats. This may be a problem for roughness shifts along vertical slopes.

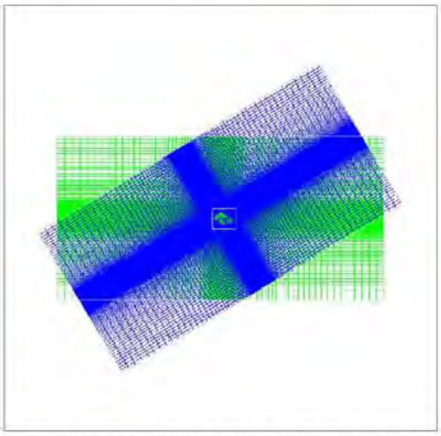


8 Risø DTU, Technical University of Denmark RANS predictions of Bolund 03/12/2009

Computational Domain (1)



One domain for all comp.



A dedicated mesh for each direction

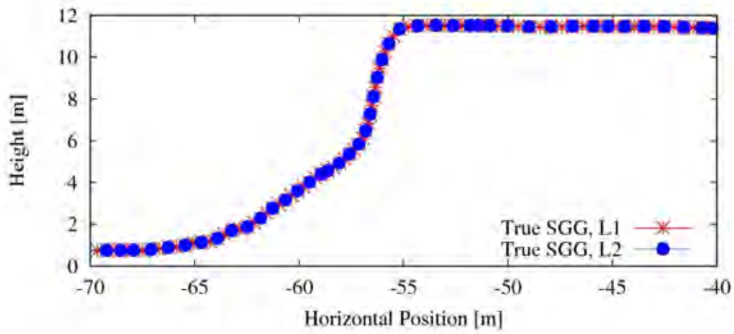
Computational Domain (2)

- Typically we have a problem of where to specify boundary conditions, especially inflow.
  - For Bolund this is not an issue
- Solutions?
  - Make a very large domain specify simple conditions at inlet
    Expensive or requires a zooming grid
  - Obtain the inflow conditions from external means
    - Measured values
    - Nested computations
    - Mesoscale model

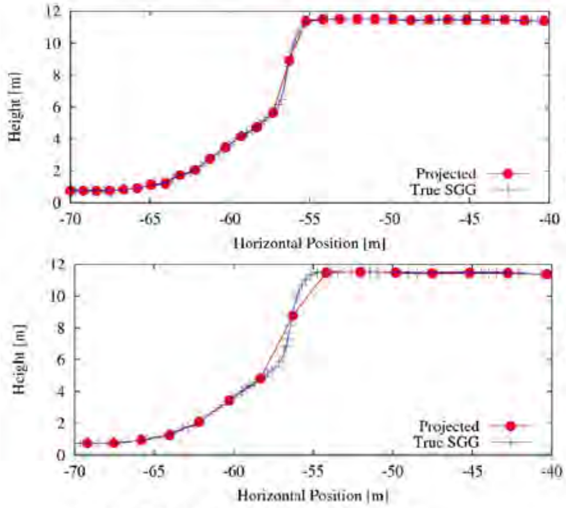
    Often the measurements or computations will not have sufficient resolution.
- For domains dedicated to specific flow directions symmetry conditions are often used at the side 'walls'. This may make them useless for studies with slightly different flow direction.

Surface Resolution (1)

- Using a true surface grid generation on the terrain surface, will allow good resolution of steep gradients. As seen below this allows good resolution even on level 2 and 3 grids.



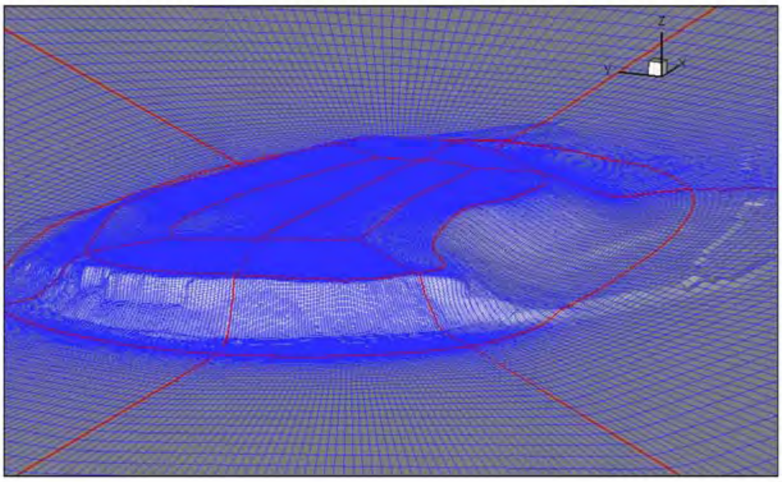
Surface resolution (2)
The problem of projected grids



Using just simple projection of a 2D surface grid onto the terrain, will naturally lead to coarse cells at steep slops in the terrain.

The grids are not well suited for grid convergence studies.

Surface Grid (1)



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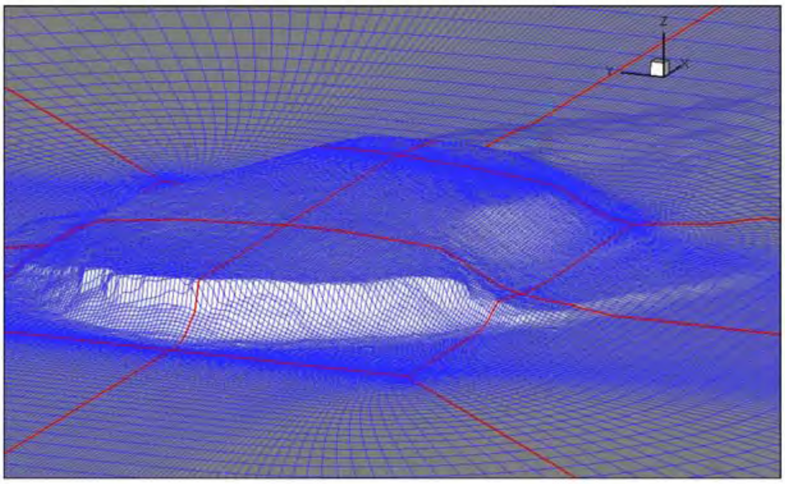
Surface Grid (2)



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Is the digital terrain correct

- And how good is the roughness estimation?

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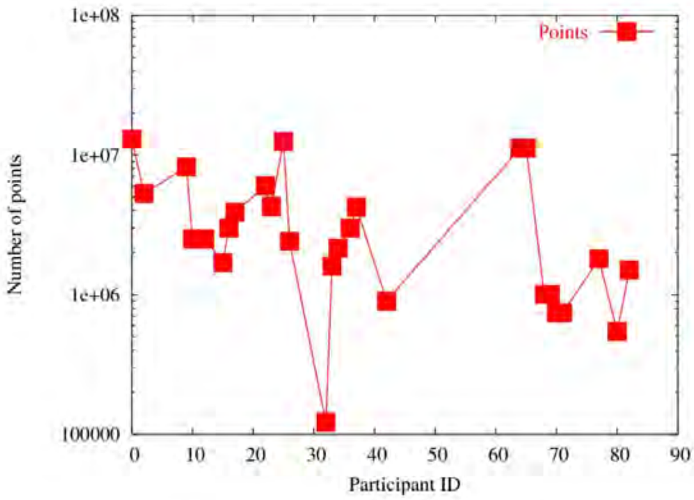
Number of points used for the simulation



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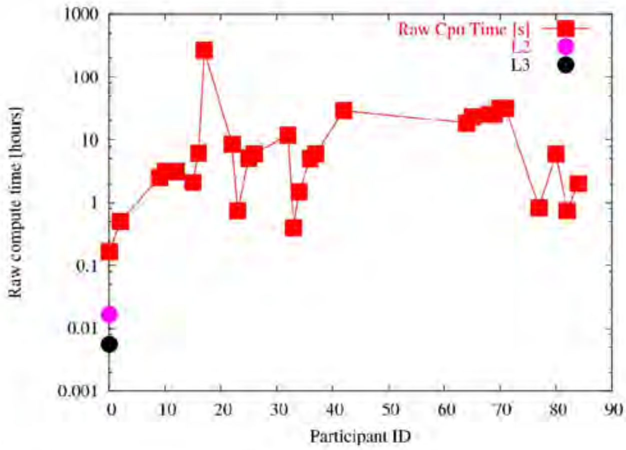
Turnaround time

Computing time may be an issue compared to linear models



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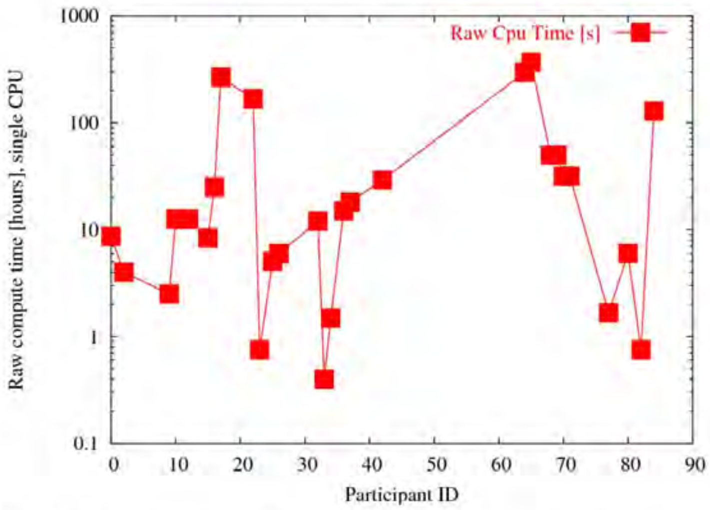
Computing time on a single Cpu



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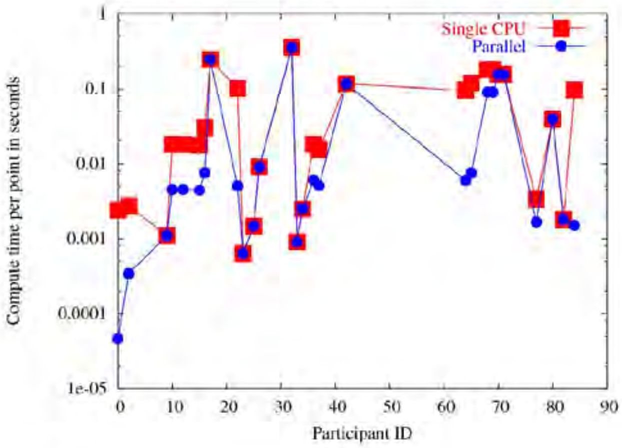
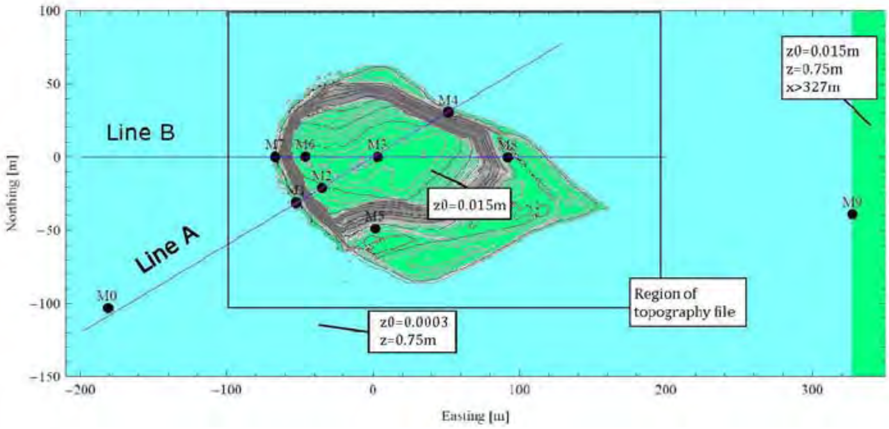
Computing Time



There is a speed difference of around 50-500 between the fastest and slowest.

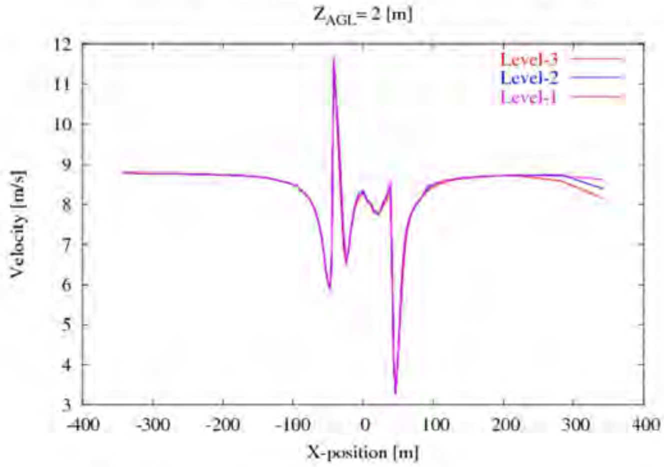
Including the parallel runs the difference is more than 5000

Setup of the masts



Grid Convergence (1)

- Flow direction 270 degrees, computations along line B.

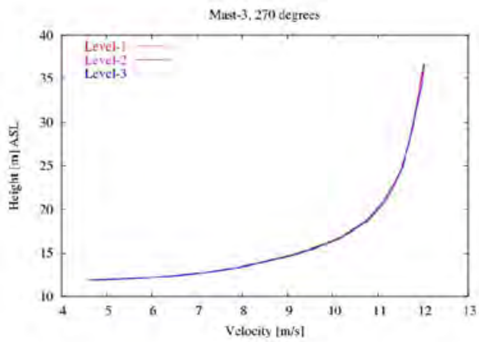


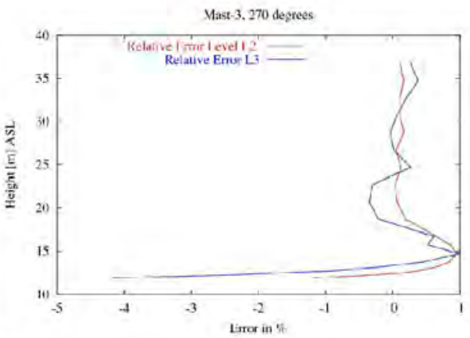
Level-3 = 0.21 Mill

Level-2 = 1.7 Mill.

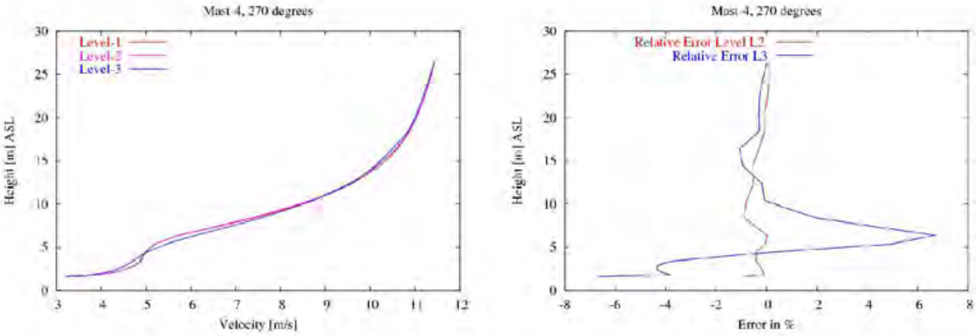
Level-1 = 13.6 Mill.

Grid Convergence (2)





Grid Convergence (3)



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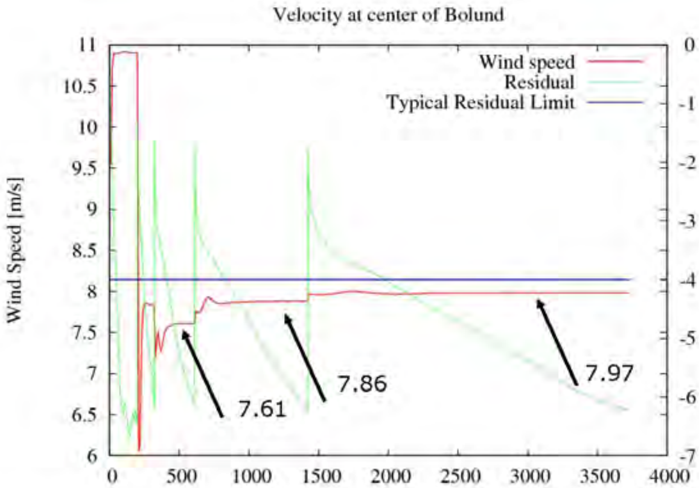
Convergence of the equations



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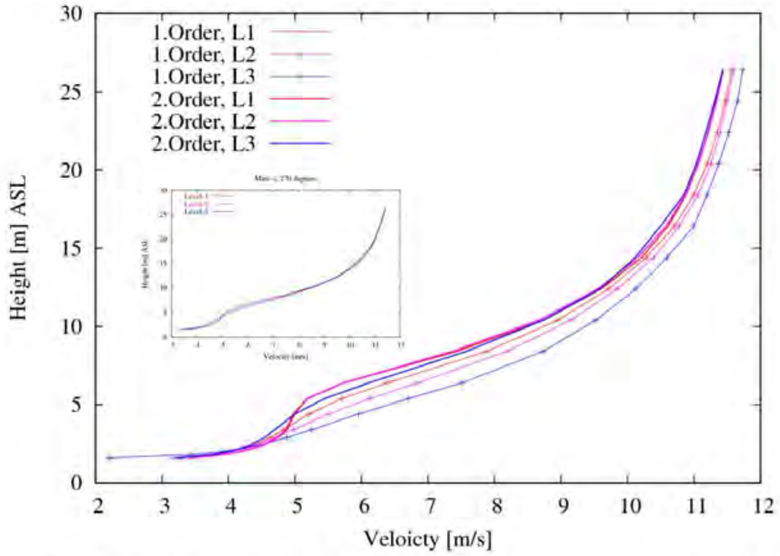
Order of accuracy



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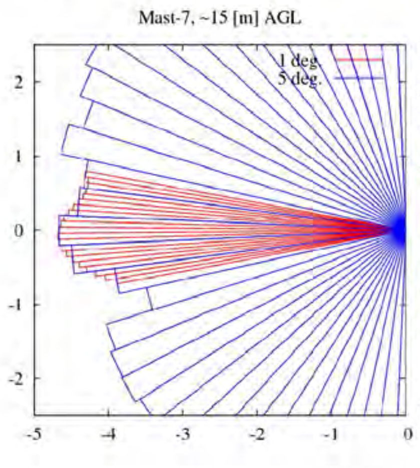
Non-linearities due to the terrain and wind direction



Computing a single flow direction using CFD we need to consider:

- Non-linear directional effects
- The frequency of the different directions

In the present location and for an inflow variation of +/- 13 degrees the variation is up to ~18%

In other places the variation can be even larger

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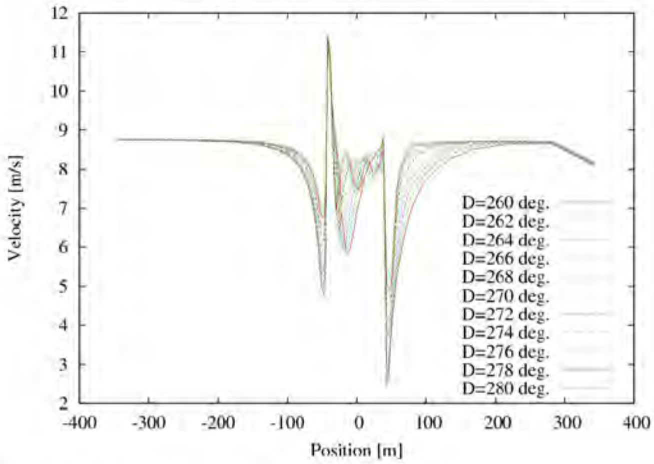
Variation of the velocity with flow angle

- Dir = 270 [deg], Height AGL = 2 [m]



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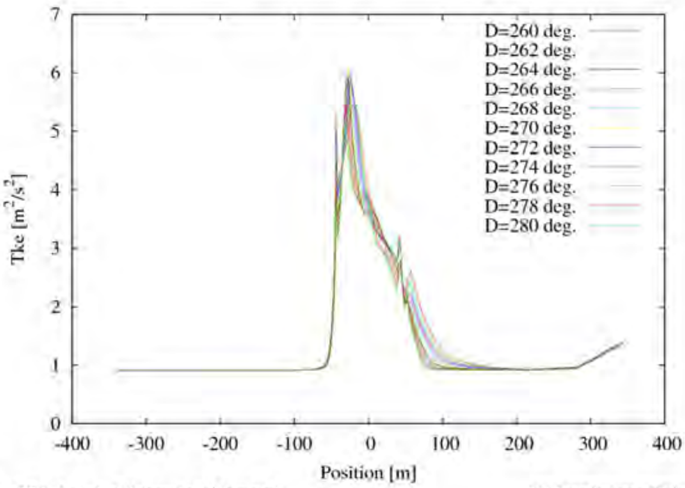
Variation of turbulence with flow angle

- Dir = 270 [deg], Height AGL = 2 [m]



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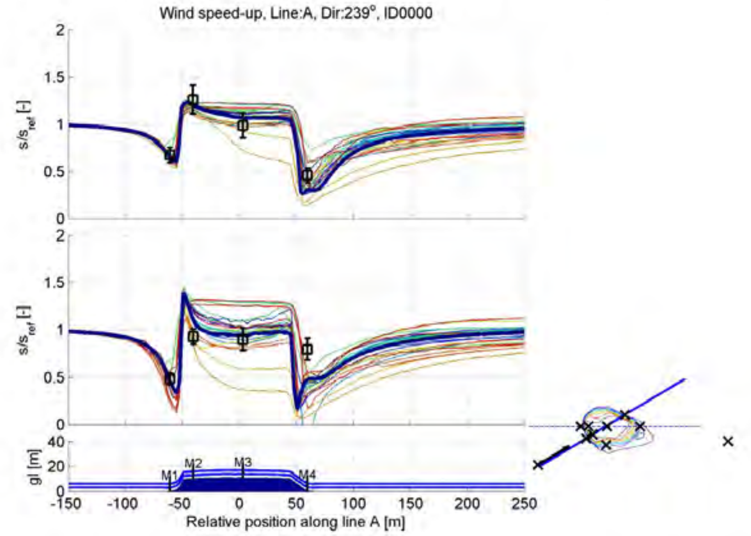
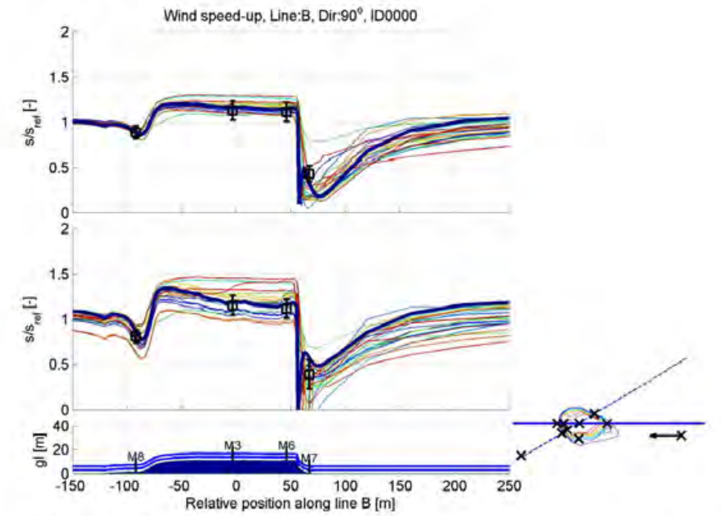
Comparison with measurements



More detailed measurements would be interesting



Conclusion

- The Bolund Blind Comparison shows that good agreement between the majority of involved RANS type models.
- Yesterday we saw that they were also able to predict the measurements with ~ 15% error.
- The typical number of points ranges from 0.5 to 4 million.
- Typical compute times between 0.01 to 0.1 sec/point.
- Grid refinement studies indicates that already with 0.21 million points a good solution can be obtained (compute time ~< 10min on one CPU)
- With these low computing times the full wind rose with 5 to 10 degrees resolution can easily be computed.

Bolund may not be typical for the majority of sites, due to the well defined inflow boundary conditions. The lack of well defined inflow BC's may severely change the conclusion of good agreement.

Hopefully further large scale experiments aimed directly at code validation will take place in the future.

Blind Comparison Simulation Cases

The description of the simulation cases for the blind comparison is found below.

The Bolund Experiment:
Blind Comparison of Codes - Wind in Complex Terrain

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The Bolund Experiment: Blind Comparison of Flow Models

1 Introduction

The Bolund experiment is a field campaign that provides a new dataset for validating models of flow in complex terrain and is the basis for a blind comparison of flow models. This document contains instructions that enable modelers to participate in the blind comparison. The deadline for returning simulation results is 31/10/09. Good luck!

2 The Experiment - Quick Overview

The Bolund experiment was performed during a three month period in 2007 and 2008. Bolund is a 12m high coastal hill located just north of Risø DTU (see Figure 1). Figure 2 gives an overview of the Bolund orography and the positions of the ten masts that supported the instrumentation. A short description of the experiment is found below. For a detailed description of the Bolund experiment please see [1].

Figure 1: Picture of Bolund taken from a 125m high measuring mast at Risø DTU.

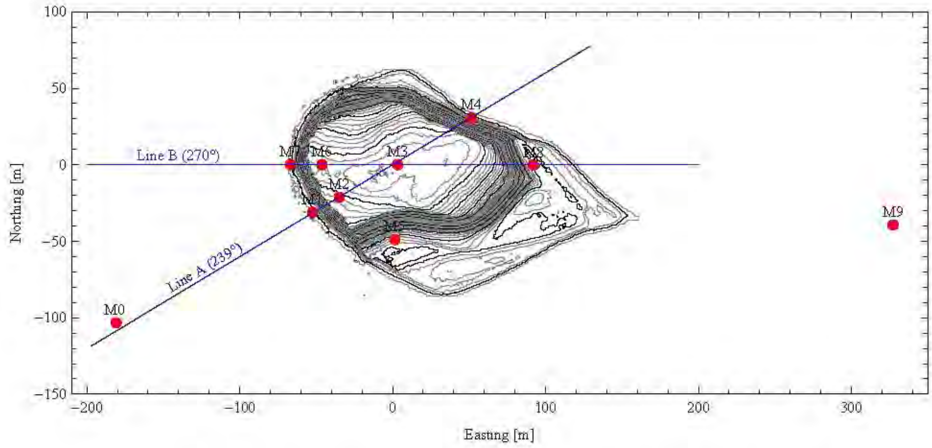

Figure 2: The Bolund orography and the positions of the ten masts

2.1 Topography Description

The topography information can be downloaded from the Bolund web page (`http://bolund.risoe.dk`) and contains four files: gridded files of the Bolund orography and roughness with 25cm resolution (`Bolund.grd`, `Bolund_roughness.grd`), a map file containing the height contours and the roughness of Bolund (`Bolund.map`) and a text file with a description of the file formats. The geometrical shape of the hill consists of a vertical escarpment that makes the Bolund hill a challenging test case for most flow solvers but the sharp change in surface roughness also adds to the complexity. The surface roughness of Bolund is described very simply in the topography files: Bolund is covered by grass with an estimated roughness length of 0.015m and for the surrounding water a roughness length of 0.0003m has been selected. The water roughness changes with wind speed, however, in order to unify the blind comparison a value of 0.0003m must be used (see Figure 3). The roughness in the topography files was updated on 01/06/09 to the values described in this document. Please ensure that you are using the correct roughness.

On figure 2 the 10 masts are numbered from 0-9. At mast M0 and mast M9 the ”undisturbed” wind conditions were measured for westerly and easterly winds respectively. The free wind conditions given below were measured at these masts. Mast M0 was placed in the sea on a platform firmly positioned on the sea bed. During the experiment the water level changed, consequently changing the measurement height on M0. This of cause complicates things somewhat. In the topography files the water level has been set to z=0.75m. The measurements used in the blind comparison cases have, among other parameters, been sorted based on water level (75cm ± 40cm) and even though the mean water level for some of the cases are slightly different than 75cm all simulations must be performed with a water level of 75cm.

The topography files only cover the region very close to Bolund (see Figure 3). Modelers must expand the map as far as they feel appropriate for their particular model,

2

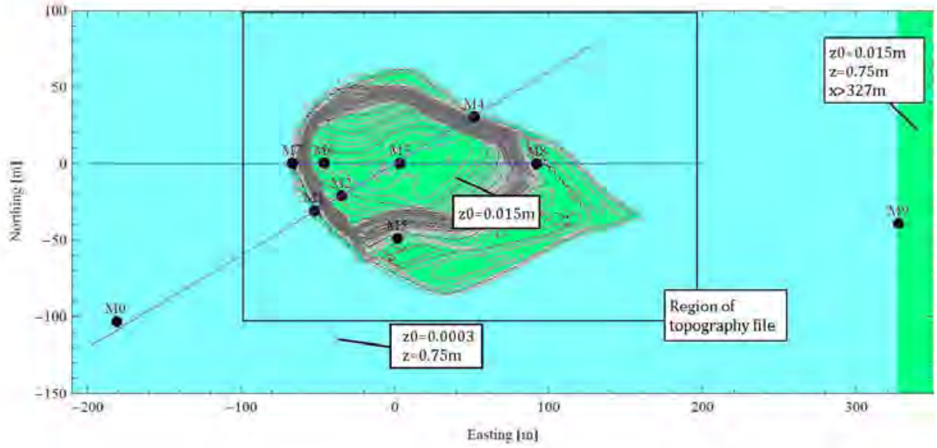

Figure 3: Definition of surface roughness and terrain height for the the blind comparison.

however, $x = \pm 400$m is the minimum. When expanding the map the terrain height / water height of 75cm should be kept and a roughness length of z0=0.0003m should be kept around Bolund. The only exception is for the eastern region ($x > 327$m) (see figure 3) where are roughness length of 0.015m should be used. The participants of the blind comparison will be asked to simulate four cases (see description below). Each of the cases will be characterized by the velocity and turbulent kinetic energy at an upstream location (reference location) where the wind is considered undisturbed by Bolund. For the experiment this location is mast M0 for westerly winds and M9 for easterly winds. For participants, the reference measurements should be applied at the inlet boundary of their modeling space even though this location does not coincide with the reference location. Participants are encouraged not to optimize their inlet boundary condition in order to achieve the measured velocity profiles at M0 and M9. The effect of this will be minimal on the final non-dimensional results.

2.2 Instrumentation description

During the campaign, velocity and turbulence were collected simultaneously from 35 anemometers (23 sonics and 12 cups) on ten masts (see Figure 2). As already described, the "undisturbed" wind was measured at mast M0 and M9. The remaining masts were located along two lines (line A and B) with a 239° and 270° direction respectively. The positions of the masts are given in Table 1. The ground levels (gl) in Table 1 (water level for mast M0) are the same as in the topography files. In the following, slightly different terrain heights may appear. This is due to changes in the water level during the experiment. However, for all blind comparison simulations the official water level of 0.75m must be used.

The masts were instrumented with a combination of sonic (S) and cup (C) anemometers. Mast M0 and M9 were instrumented with 4 cups in approximately 2m, 5m, 9m

3

Table 1: The positions of the masts. The real ground level for M9 is 1.39m., however, in order to simplify the blind comparison this height has been changed to 0.75m

Mast ID.	x (E) [m]	y (N) [m]	gl [m]
M0	-180.832	-103.267	0.75
M1	-52.426	-30.987	0.78
M2	-34.840	-21.110	10.80
M3	3.220	0.000	11.66
M4	51.458	30.612	1.37
M5	1.502	-48.926	2.59
M6	-46.121	0.242	11.47
M7	-66.887	0.016	0.81
M8	92.009	-0.136	2.00
M9	327.326	-39.296	0.75

an 15m height in order to measure the mean velocity profile. Additionally, sonics were placed in 5m height on both masts to measure turbulence. An additional sonic was placed in 12m height at M0 during the experiment. The measurements at these masts will provide the wind input for the blind comparison. Temperature measurements were performed at M0 and M9. In addition to the heat fluxes measured by the sonics these measurements enabled the data to be sorted based on temperature stratification (only neutral conditions are used in the blind comparison). The other masts were mostly instrumented with sonics and all masts had sonics in 2m and 5m height. Table 2 gives an overview of the instrumentation. During the experiment some masts were instrumented with additional sonics, e.g. at M2 in 1m and 3m height.

Table 2: An overview of the instrumentation during the experiment. The heights are only approximate. C - Cup anemometer, S - Sonic anemometer, L - Lidar.

Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

4

3 The Blind Comparison

This section describes the four cases (wind directions) that modelers must simulate in the Bolund blind comparison. Three of the cases are for westerly wind directions and the final case is for wind from the east. The description below defines how the simulations should be conducted and must be read carefully. In order to get an accurate picture of how the different flow models behave all modelers should use the same boundary conditions. This is necessary in order to minimize user errors and unify the comparison. Surely, boundary conditions cannot be controlled freely for all the flow models that participate in the comparison, however, **each modeler must strive to use the specified input as closely as possible**.

3.1 definitions

The coordinate system is a right handed regular East (u in the x-direction)- North (v in the y-direction) coordinate system. The vertical axis is pointing upwards for positive values. The coordinate center has been placed at (694682.098; 6177441.825) (UTM WGS84 zone 32) and z=0 is 0.75m below the local water level. The coordinate center has been changed in order to avoid round off errors and must be kept. The wind direction (where the wind comes from) is defined with 0° true north and increasing clockwise, i.e. 270° denotes westerlies. The 10min averaged velocity vector is **u**=(u,v,w) and the total velocity (wind speed), s, is defined by,

$$s = \left(u^2 + v^2 + w^2\right)^{0.5} \tag{1}$$

The r.m.s (root mean square) or standard deviation of u is denoted by u' and is also found from 10min averages. It is important to stress that all statistics used in the blind comparison are based on 10 minutes averages. The turbulent kinetic energy, TKE, is defined to be half the sum of mean-square fluctuations,

$$TKE = 0.5\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right) \tag{2}$$

The shear stress, τ, is an important scaling parameter and from this the friction velocity, u_*, is defined

$$u_*^2 = \tau/\rho = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/2}, \tag{3}$$

where ρ is the air density. Finally, we define the Monin-Obukhov length,

$$L = -\frac{u_*^3\theta}{g\kappa\overline{w'\theta'}} \tag{4}$$

where κ is the von Karman constant, g is the acceleration of gravity and θ is the potential temperature. A lowercase 0, e.g. u_{*0}, denotes that the specific value is evaluated at an upstream reference location (for the experiment at mast M0 or M9 depending on wind direction).

3.2 Simulation cases

Participants are asked to provide results for four simulation cases. The three first cases are three easterly wind directions (270°, 255°, 239°), otherwise with the same free wind conditions (the wind is coming from the sea). The fourth case is with the wind from the east (90°) where the upstream terrain has a somewhat larger roughness. The four cases are listed in Table 3 where the wind direction, roughness length and TKE of the free wind are listed. The roughness in Table 3 is used when defining the free stream velocity (see below), the roughness defined in the topography files (and figure 3) should be kept. A friction velocity is also given in Table 3. If participants need to specify a specific wind speed / friction velocity in their model then this is the value that should be used.

Table 3: The four simulation cases

Case	Wind direction [°]	Roughness length, z_0 $[m]$	TKE_0/u_{*0}^2 $[-]$	u_{*0} $[m/s]$
1	270	0.0003	5.8	0.4
2	255	0.0003	5.8	0.4
3	239	0.0003	5.8	0.4
4	90	0.015	5.8	0.5

Participants should if possible apply the well-known logarithmic velocity profile at their reference location / computational boundary,

$$s = \frac{u_{*0}}{\kappa} \log\left(\frac{z_{agl}}{z_0}\right) \tag{5}$$

where $\kappa = 0.4$ and the surface roughness (z_0) and friction velocity (u_{*0}) is given in Table 3. z_{agl} is the height above ground level i.e. $z_{agl} = z - 0.75$m. Similarly, the turbulent kinetic energy (if available in the model) should be prescribed as constant with height with the following value,

$$\frac{TKE}{u_{*0}^2} = 5.8 \tag{6}$$

The profiles of velocity and TKE that should be used in the blind comparison are shown on Figure 4. The actual measured values are also shown on Figure 4 and are also given in Table 4. These measurements and all other measurements used in the blind comparison are for neutrally stratified conditions ($|1/L| < 0.004$).

In order to unify comparisons participants should use the same air properties if these are needed as input for the models. Simulations should be run with dry air with a density at sealevel of $\rho = 1.229$kg/m^3, dynamic viscosity of $\mu = 1.73 \cdot 10^{-5}$kg/ms and temperature of $T = 15$°C (zero heat flux $\overline{w'\theta'} = 0$). Furthermore the gravitational acceleration is $g = 9.81$m/s^2 and a coriolis parameter of $f = 1 \cdot 10^{-4}$s^{-1} should be used if needed.

6

Table 4: Free wind conditions at M0 for case 1-3 (wind direction is 270°, 255°, 239°) and free wind conditions at M9 for case 4 (wind direction is 90°). The table gives the mean velocity from cups and sonics and the turbulent kinetic energy from sonics. The numbers in the brackets are the standard deviations. The heights of the instruments are given in the global coordinate system and as the height above water level.

Inst. type	x $[m]$	y $[m]$	z $[m]$	z_{agl} $[m]$	s/u_{*0} $[-]$	TKE/u_{*0}^2 $[-]$
			CASE 1			
Cup	-180.83	-103.27	3.1	2.3	21.88 (1.68)	-
Cup	-180.83	-103.27	6.1	5.3	23.39 (1.70)	-
Cup	-180.83	-103.27	10.1	9.3	24.57 (1.70)	-
Cup	-180.83	-103.27	16.1	15.3	25.82 (1.71)	-
Sonic	-180.83	-103.27	6.1	5.3	22.73 (1.73)	5.43 (0.72)
Sonic	-180.83	-103.27	13.1	12.3	24.69 (1.66)	5.38 (0.83)
			CASE 2			
Cup	-180.83	-103.27	3.1	2.4	23.06 (1.34)	-
Cup	-180.83	-103.27	6.1	5.4	24.47 (1.40)	-
Cup	-180.83	-103.27	10.1	9.4	25.60 (1.41)	-
Cup	-180.83	-103.27	16.1	15.4	26.73 (1.45)	-
Sonic	-180.83	-103.27	6.1	5.4	24.11 (1.40)	6.31 (0.99)
Sonic	-180.83	-103.27	13.1	12.4	25.10 (1.40)	6.14 (1.13)
			CASE 3			
Cup	-180.83	-103.27	3.1	2.4	23.05 (2.35)	-
Cup	-180.83	-103.27	6.1	5.4	24.40 (2.48)	-
Cup	-180.83	-103.27	10.1	9.4	25.56 (2.64)	-
Cup	-180.83	-103.27	16.1	15.4	26.67 (2.76)	-
Sonic	-180.83	-103.27	6.1	5.4	24.31 (2.49)	6.55 (1.10)
Sonic	-180.83	-103.27	13.1	12.4	25.85 (2.67)	6.56 (1.31)
			CASE 4			
Cup	327.33	-39.30	-	1.9	13.31 (1.28)	-
Cup	327.33	-39.30	-	5.0	14.90 (1.38)	-
Cup	327.33	-39.30	-	9.0	15.30 (1.41)	-
Cup	327.33	-39.30	-	15.6	16.69 (1.52)	-
Sonic	327.33	-39.30	-	5.0	14.66 (1.37)	6.74 (0.87)

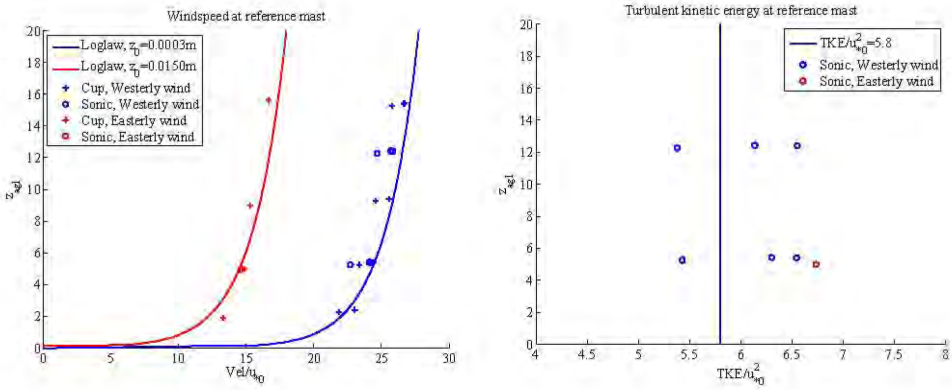

Figure 4: Inlet profiles of velocity and TKE. Symbols are measurements and full lines are the input that should be used by participants. The blue color are for cases 1-3 while red is for case 4.

3.3 Simulation Output

For each of the 4 cases specified in Table 3, participants are asked to provide the model results in simple text files (ascii format) with the output as described below. The filename of the 4 files must follow the conversion *codenumber_casenumber.dat*. For instance a participant that has received the "code number" of ID0001 should provide 4 files named ID0001_1.dat, ID0001_2.dat, ID0001_3.dat and ID0001_4.dat. The files should be submitted to Risø DTU before November 1, 2009 by email to andh@risoe.dtu.dk. Please attach the 4 result files to the email and write the model number in the subject line.

The output that should be provided in the result files and their units are given in Table 5. Participants are asked to extract their model results in 600 points given in the file *output_points.dat*. Each of the 600 lines in *output_points.dat* consists of a x,y and z - values. The result files (*codenumber_casenumber.dat*) should also consist of 600 lines in a similar format but each line should consist of the quantities in the following order: x, y, z, s, u, v, w, TKE, $\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$, u_* (see Table 5). The result files therefore consists of 600 lines (one for each point) and 12 columns (one for each quantity). Some models are only capable of predicting the wind speed, for such models the result files should still have 12 columns but column 8-12 should consist of the letters "nan". Similarly, if a model can predict wind speed and TKE but not the variances ($\overline{u'u'}$, $\overline{v'v'}$, $\overline{w'w'}$ and u_*) then column 9-12 should consist of "nan". Most models that participate cannot predict the variances so most result files will consist of 7 or 8 columns with numbers and 4 or 5 columns with the letters "nan". The files should not contain a text header. For all four cases (the four wind directions) the results should be given in the already defined coordinate system. For case 4 where the wind is from the east the u-component of the velocity will have a negative sign. Finally, all quantities should be given SI units i.e. meters and seconds.

Experimental modelers are only required to simulate case 1 and 3 and have fewer result points. If you need to be registered as an experimental modeler then please write an email to andh@risoe.dtu.dk.

Table 5: Output quantities and measurement conventions.

Quantity	quantity description	Convention
x	Position in the east/west direction [m]	See definition section
y	Position in the north/south direction [m]	See definition section
z	Vertical position [m]	See definition section
s	The total velocity [m/s]	See Equation 1
u	East/west component of the velocity [m/s]	See definition section
v	North/south component of the velocity [m/s]	See definition section
w	Vertical component of the velocity [m/s]	See definition section
TKE	Turbulent kinetic energy [m^2/s^2]	See Equation 2
$\overline{u'u'}$	East/west component of TKE [m^2/s^2]	See definition section
$\overline{v'v'}$	North/south component of TKE [m^2/s^2]	See definition section
$\overline{w'w'}$	Vertical component of TKE [m^2/s^2]	See definition section
u_*	Local friction velocity [m^2/s^2]	See Equation 3

References

[1] A. Bechmann, J. Berg, M.S. Courtney, H.E. Jrgensen, J. Mann, and N.N. Srensen. The bolund experiment: Overview and background. Technical Report Risø-R1658(EN), Risø DTU, National Lab., Roskilde, Denmark, 2009.

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